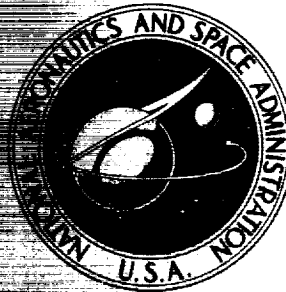


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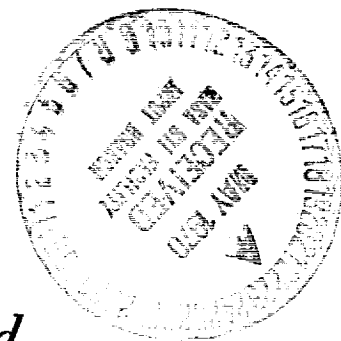


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OTED FLIGHT SIMULATORS**

Stanley F. Schmidt and Bjorn Conrad



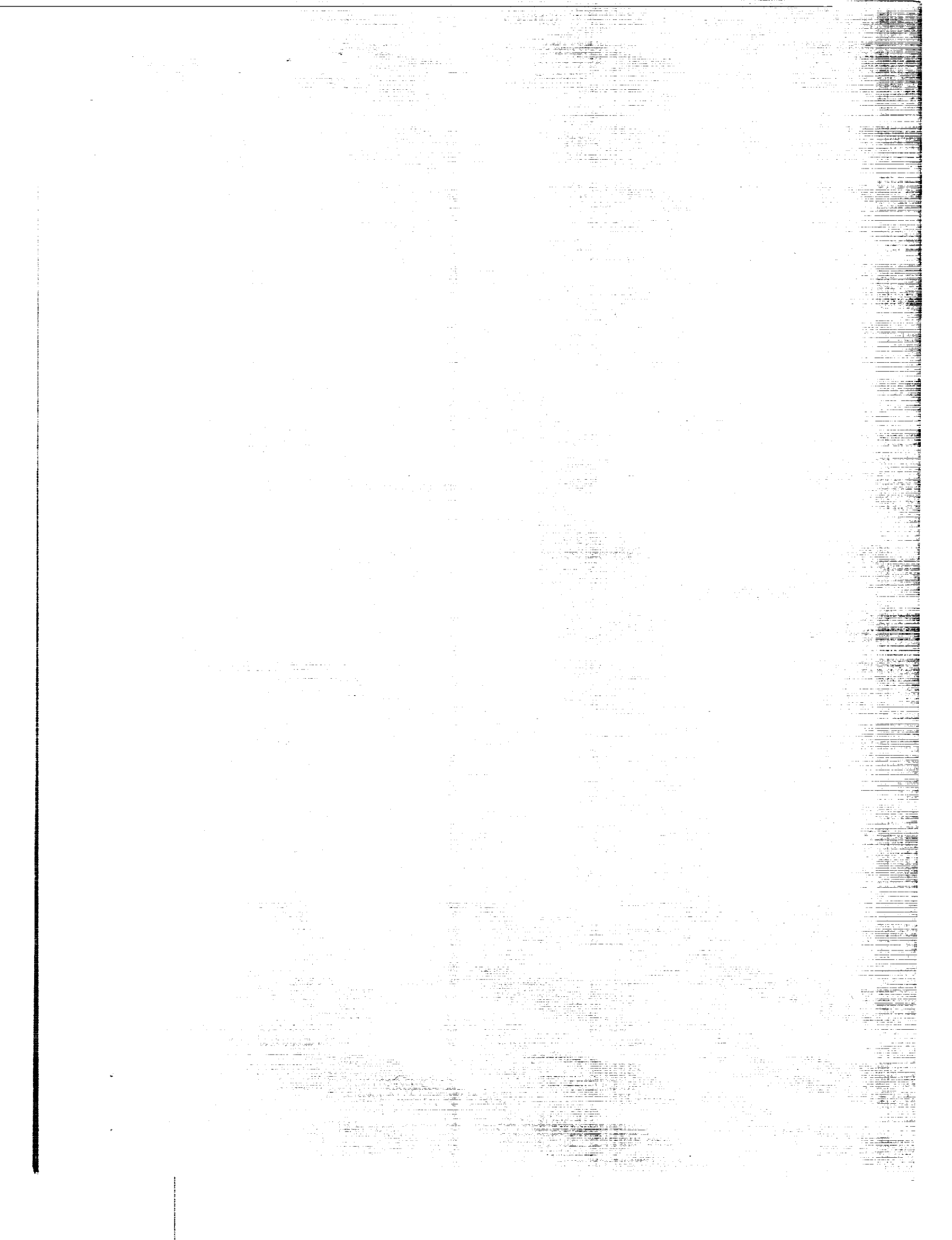
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MOTION DRIVE SIGNALS
FOR PILOTED FLIGHT SIMULATORS

By Stanley F. Schmidt and Bjorn Conrad

Prepared under Contract No. NAS 2-4869 by
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SUMMARY

An important aspect of many piloted flight simulators is their ability to provide realistic motion cues. Since such simulators are constrained to move within the confines of their mechanical drive systems, they cannot duplicate all the motions (and hence all the motion cues) associated with a real aircraft. In order to use the limited motion capabilities of a simulator effectively it is thus necessary to a) determine which motion cues are important to a pilot; b) ascertain which cues are attainable within the drive system capabilities of a simulator; c) synthesize logic for commanding motion achievable by the drive system and realistic to a pilot.

This report summarizes a mathematical approach to this problem and presents logic synthesized for the Ames All-Axis Motion Generator. Both the theory developed and the logic presented should be applicable to a wide variety of motion simulation problems.

SYMBOLS

f	specific force vector on pilot in a simulated aircraft
\hat{f}	specific force vector on pilot in cab of simulator
g	gravity acceleration on pilot in a simulated aircraft
\hat{g}	gravity force vector on pilot in cab of simulator
$G(s)$	transfer function: Laplace transform
K	gain or matrix of gains (as seen from context) with subscript identifiers
M	a 3 x 3 matrix relating simulator gimbal angle rates to body rotation rates
r	position vector associated with the simulated aircraft
\hat{r}	position vector of the cab of the motion generator
$T_{c/i}$	a 3 x 3 orthonormal transformation matrix that transforms a vector coordinatized in frame i to one in c , e.g.,

$$r_c = T_{c/i} r_i$$

ω	aircraft angular rotation rate. In body frame
----------	---

$$\omega_c \triangleq \begin{pmatrix} p \\ q \\ r \end{pmatrix} = \begin{pmatrix} \text{roll} \\ \text{pitch} \\ \text{yaw} \end{pmatrix} \quad \text{body rates}$$

$\hat{\omega}$	simulator cab rotation rates
----------------	------------------------------

$\begin{pmatrix} \phi \\ \theta \\ \psi \end{pmatrix}$	aircraft Euler angles; roll, pitch and yaw respectively
--	---

$\begin{pmatrix} \hat{\phi} \\ \hat{\theta} \\ \hat{\psi} \end{pmatrix}$	simulator gimbal angles
--	-------------------------

ζ Damping ratio

ω_n natural frequency

$\dot{a} \triangleq \frac{da}{dt}$ indicates time derivatives of vector components in inertial coordinates

Subscripts

i vector coordinatized in the inertial reference frame, e.g.,

$$r_i = \begin{pmatrix} r_{i1} \\ r_{i2} \\ r_{i3} \end{pmatrix} \triangleq \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}$$

c vector coordinatized in the aircraft cockpit or the simulator cab reference frame

SECTION 1

INTRODUCTION

Piloted flight simulators are used extensively for both research⁽¹⁾ and pilot training purposes. It is well known^(2,3,4,5) that the addition of motion in these simulations provides realism and gives a greater consistency of research results between simulations and flight tests. Motion simulators have highly restricted movement, however, and techniques which make optimal usage of this restricted motion are not well understood.

The command signals for a motion simulator cannot be taken directly from a computer simulation of a real aircraft's motion but first, must be modified by logic which is traditionally referred to as "washout" circuits. The traditional approach⁽⁶⁾ to designing such circuits has been empirical, using subjective pilot opinion as a measure of its success.

This report summarizes the results of a research investigation whose overall objective was to improve the techniques for designing such circuits. A specific objective was to provide washout logic for the Ames All-Axis Motion Generator described in Appendix A. These objectives can be accomplished only after examining some closely related problems. These include finding answers to such questions as:

- 1) What type of motion is important to the pilot?
- 2) At what level does anomalous motion become distracting?
- 3) How can the effectiveness of washout circuits be tested?

Hence a great deal of effort was expended on these areas as well as on the design of operational logic.

Section 2 presents a brief review of the overall motion simulation problem and some fundamental assumptions about pilot sensed motion. This section also presents mathematical descriptions of motion constraints, pilot sensed motion cues, etc., which are fundamental to understanding the principles of washout circuit design.

Section 3 describes traditional solutions to washout circuit design, generally applicable to motion simulators having one to three degrees of freedom. Section 4 expands the traditional ideas to multi-degree of

freedom simulators. Coupling problems associated with the latter are investigated and some new concepts are combined with the traditional ones to obtain two multi-degrees of freedom washout circuit designs. The first design may be formally thought of as an extension of traditional techniques, while the second design utilizes coordinated rotational and translational signals to obtain very accurate longitudinal and lateral force cues.

Section 5 discusses the overall problem associated with experimental validation of washout circuitry. The various considerations discussed there led to the development of a simulated formation flying task. The results of an evaluation of this task are presented in this section. These results compare fixed base (no motion) and nearly ideal motion. Section 6 reviews the overall research investigation and makes several recommendations for continued research.

SECTION 2

MOTION SENSING AND SIMULATION

2.1 Review of Overall Problem. - In order to obtain a perspective on the work discussed in this report a brief review of a piloted flight simulator, with specific emphasis on the inherent difficulties with which this research is concerned, is presented.

Conceptually a piloted flight simulator consists of the following blocks:

1. A cockpit ("cab") which can be moved about via commands issued to servo drive systems.
2. Airplane control devices (stick, rudder pedals, etc.) located in the cab.
3. A computer which takes input signals from the controls and solves the aircraft's equations of motion to determine its states (e.g., positions, velocities, attitudes and angular velocities).
4. Assorted aircraft instrumentation and other visual indicators which provide a measure of the aircraft's state (as determined by the computer) to the pilot.

The instruments and visual display can be commanded to move in accordance with the computed aircraft state. Ideally, the cab would also be commanded to move about in accordance with the states that the real aircraft would possess. Generally, it is impossible to do this since the cab is mounted in a mechanical structure with limited motion. In particular, such a cab can only move a few feet in any direction with limited velocity and accelerations. Similar limitations exist on angular rotations and rotation rates.

Now the following dilemma arises. The pilot manipulates the controls of the simulator. The computer determines the resultant motion of the aircraft being simulated and sets the visual display to show this motion. The computer also commands the cab to move, preferably just as the aircraft would. However, since only limited motion of the cab is possible some modification of the computer motion is necessary before it is used to command cab motion. Otherwise, the cab would be driven into its limits and hence give totally erroneous motions to the pilot.

The object of this research project was to investigate ways of using the computed motion values to obtain signals representing similar motions compatible with the cab's limitations. In general, the movement of the cab must be inconsistent with the pilot's instruments and other visual displays. However, a pilot's motion senses are also limited and he may attach far more importance to some motion cues than others. The most desirable signal modification scheme would involve choosing an allowable motion which gives the pilot the best sensed motion cues possible. Under some circumstances, for example, the best solution could be to give the pilot no motion at all. This may occur when any allowable cab motion would be too inconsistent with visually indicated motion and hence unrealistically confusing to the pilot.

Two major problem areas are now defined. First, which motions can a pilot sense and which are important to flying in a particular aircraft performing a given task? Second, what logic scheme (if any) will produce reasonable pilot sensations compatible with the cab motion limitations? Answers to these questions require a great deal of experimental as well as mathematical development and the results frequently can be given only qualitative interpretation. The design of such experiments and of evaluation procedures which interpret their outcome are in themselves difficult tasks.

2.2 Pilot Sensed Motion. - The exact quantities sensed by a pilot's motion perceptive organisms are not completely understood. However, empirical knowledge combined with theoretical and practical considerations

leads to the assumption¹ that a pilot can "sense"² the same quantities as can be measured by three linear and three rotational accelerometers. Subsequent paragraphs discuss some of the consequences of these assumptions with regard to the motion simulation problem.

Translational Motion Sensing

A linear accelerometer does not measure acceleration but rather the difference between acceleration and gravitation. This difference is called specific force in inertial navigation literature (see reference (8)). Three appropriately mounted linear accelerometers measure the specific force vector (3 components) which is defined here as the positive sum of all non gravitational forces per unit mass.

The use of the specific force vector as the "sensed" quantity provides considerable convenience in later mathematical development. To develop appropriate equations we need consider quantities which depict what linear accelerometers would measure in the particular situation. For example, if one were seated in the cockpit of an airplane on the ground the specific force is one gravitational unit, $1g$, directed upward. This is the force restraining the body from accelerating along the direction of gravity.

Since position or velocity are not sensed by the pilot's motion perceptive organisms, initial conditions on these quantities may be selected to satisfy simulation constraints. For example, to a good approximation for aircraft, constant velocity motion may be simulated by a cab at rest on the ground.

¹References 5 and 7 contain some theoretical and empirical results which aid in justifying the assumption.

²The word "sense" has been used since it is doubtful that a pilot can gauge magnitude and directions of the motions very accurately. He also has threshold levels below which he has very little or no perception of motion.

Rotational Motion Sensing

Although rotational acceleration is sensed by the pilot we can also consider rotational rate as an equally valid quantity in mathematical development. That is, if rotational rates are the same in the motion generator as they were in an aircraft then the rotational accelerations would also be the same. We have chosen to work with rotational rates herein since it tends to simplify some of the mathematical development. This means that only initial attitudes may be selected to satisfy simulation constraints. As will be seen later, the initial attitude of the simulator might be selected to provide an appropriate initial specific force vector.

Mathematical Development

The subsequent paragraphs will develop some of the fundamental equations relevant to future discussion. Embodied in the development is the assumption that the aircraft dynamics will be simulated on a computer. Hence, we can select the appropriate quantities from the simulation to serve as input to our motion drive equations. The quantities of interest are:

- 1) The three components of force per unit mass (the specific force vector) that would act on the pilot at the cockpit location in the simulated aircraft.

and

- 2) the three components of rotation rate that would act on the pilot at the cockpit location in the simulated aircraft.

The basic notion is that if three linear accelerometers and three rate gyros were mounted in the motion generator cab and their recorded time histories matched (1) and (2), then the motion simulation is perfect.

Since we are dealing with three component quantities the development will utilize 3 component vectors and coordinate frames in which the vectors are defined. The development will use many of the fundamentals given in reference (8).

The two primary coordinate systems used in this report are

- 1) a local tangent plane system whose origin is the center of the pit in which the simulator cab moves about (see Appendix A) and
- 2) a system with its origin at the pilot's location in the simulator cab and whose direction is always aligned with the cab.

These two coordinate systems are depicted with their basis vectors in Figure 2.1. Figure 2.1a illustrates that the cab-reference is selected in the same sense as the cockpit reference in the simulated aircraft.

Subsequent discussion uses the terminology longitudinal, lateral and normal forces. These are the forces per unit mass acting along the \vec{c}_x , \vec{c}_y , and \vec{c}_z basis vectors, respectively, shown in Figure 2.1a. The positive direction of the rotation rates illustrated in Figure 2.1a are in accordance with the conventional right hand rule.

Since we are dealing with aircraft simulation problems where earth rotation factors are negligible, the approximation that a local tangent plane is an inertial reference is made. We also assume that gravitation acts along the down direction \vec{i}_3 of Figure 2.1b and has a constant magnitude.

The subscripts c or i will be used to indicate whether a quantity is defined in the cab or inertial frames of Figure 2.1. Also, to denote the difference between the quantities sensed by the pilot in the motion generator and quantities of the simulated aircraft we shall use the following

- (\wedge) - means quantity in the motion generator
- () - means quantity in the simulated aircraft.

With these assumptions and definitions Newton's equations for the translational motion of the simulated aircraft are

$$\dot{\vec{r}}_i = \vec{f}_i + \vec{g}_i \quad (2.1)$$

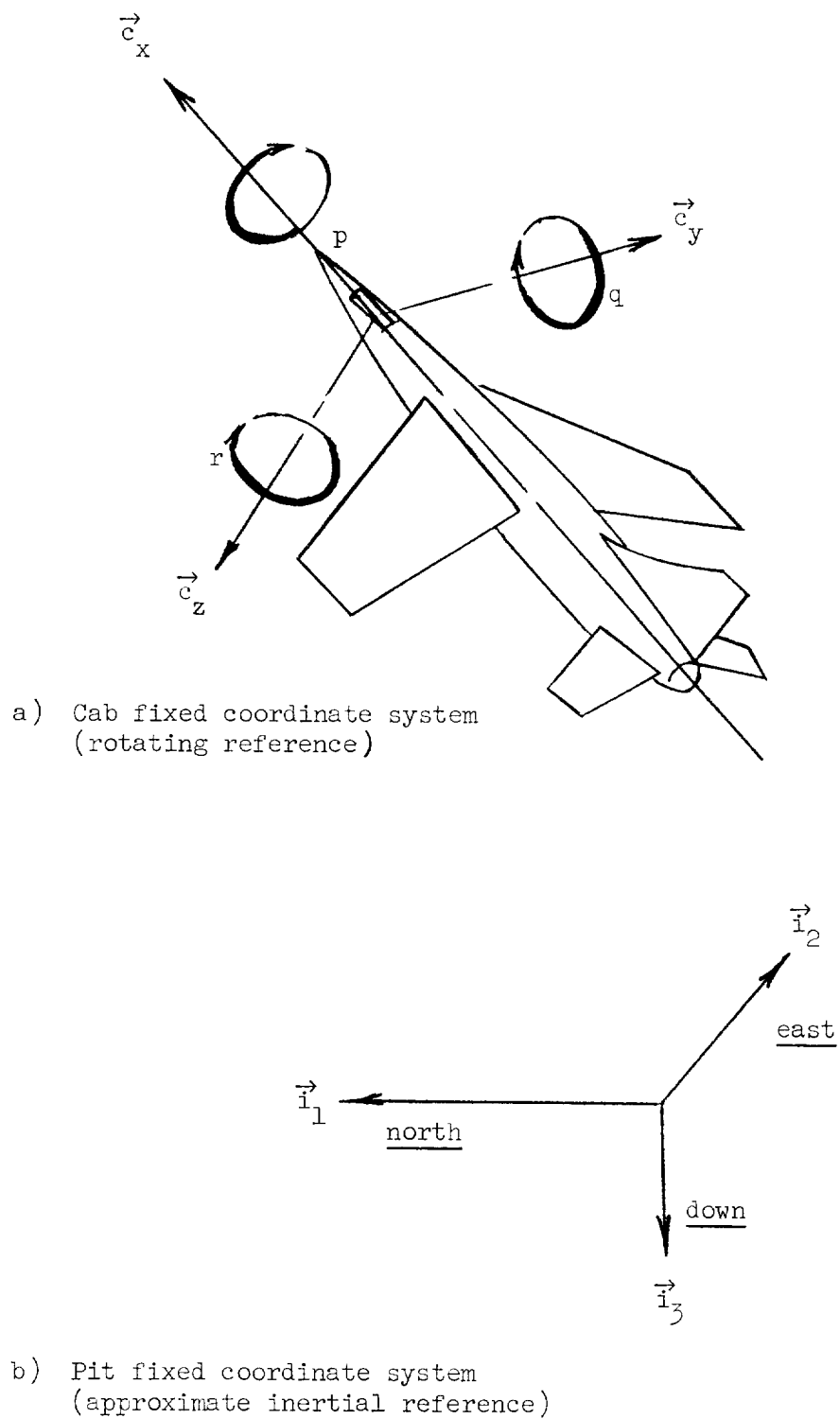


Figure 2.1 Illustration of Coordinate Systems

where

f_i = specific force vector at the pilot's location in the simulated aircraft

r_i = position vector of the cockpit relative to the reference origin

g_i = gravitational acceleration

$$\approx \begin{pmatrix} 0 \\ 0 \\ 32.2 \end{pmatrix} \text{ ft/sec}^2$$

Similarly, the equations for the translational motion of the cab are

$$\ddot{\hat{r}}_i = \hat{f}_i + g_i \quad (2.2)$$

where

\hat{f}_i = the specific force vector sensed by the pilot in the motion generator

\hat{r}_i = the position of the cab of the motion generator with reference to the origin. The origin for the All-Axis Motion Generator is the approximate center of an 18 ft cube (see Appendix A).

The cab translational motion is produced by position command signals, \hat{r}_i . Hence if we want to cause a given specific force time history for the cab, we must compute, $\ddot{\hat{r}}_i$, of equation (2.2) and integrate twice to obtain the position command time history. For example, if we had

$f_c(t)$ = desired specific force time history in the cab reference frame

Then by a double integration of

$$\ddot{\hat{r}}_i = T_{i/c}(t)f_c(t) + g_i \quad (2.3)$$

One would obtain the cab position drive signals for causing the pilot in the cab to sense $f_c(t)$ (providing motion generator constraints were not reached). In equation (2.3),

$T_{i/c}(t)$ = the orthogonal transformation between the cab and inertial reference frames. It is time dependent if the rotation rates are not zero.

The cab's rotational motion is obtained by means of gimbal angle command signals. A rotation sequence which carries the i frame into the c frame can be found from the gimbal angles by

- 1) pitching about the \vec{i}_2 axis of Figure 2.1b through the angle $\hat{\theta}$ (pitch gimbal angle)
- 2) yawing about the new \vec{i}_3 axis by an angle $\hat{\psi}$ (yaw gimbal angle)
- 3) rolling about the new \vec{i}_1 axis by an angle $\hat{\phi}$ (roll gimbal angle)

Figure 2.2 depicts each of these rotations and the intermediate frames they define. The gimbal angle rates illustrated on the figure each contribute to the total rotation rate vector, $\hat{\omega}_c$. With reference to the figure the total rate in the cab reference is

$$\hat{\omega}_c = T_{c/i} T_{i''/i} \hat{\omega}_{i''} + T_{c/i} \hat{\omega}_{i''} + \hat{\omega}_c \quad (2.4)$$

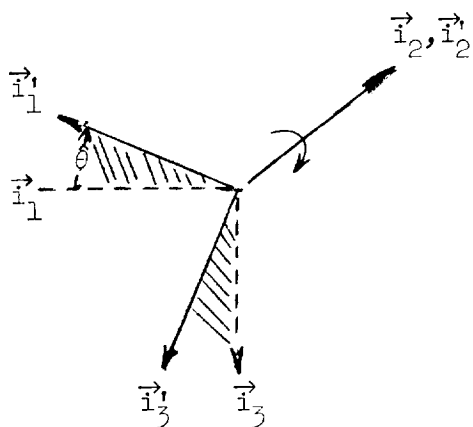
Utilizing the transformations and rates as defined in Figure (2.2) in equation (2.4) gives

$$\begin{aligned} \hat{\omega}_c = \begin{pmatrix} \hat{p} \\ \hat{q} \\ \hat{r} \end{pmatrix} &= \begin{bmatrix} \dot{\hat{\theta}} \sin \hat{\psi} + \dot{\hat{\phi}} \\ \dot{\hat{\theta}} \cos \hat{\psi} \cos \hat{\phi} + \dot{\hat{\psi}} \sin \hat{\phi} \\ \dot{\hat{\theta}} \cos \hat{\psi} \sin \hat{\phi} + \dot{\hat{\psi}} \cos \hat{\phi} \end{bmatrix} \\ &= \begin{bmatrix} 1 & \sin \hat{\psi} & 0 \\ 0 & \cos \hat{\psi} \cos \hat{\phi} & \sin \hat{\phi} \\ 0 & -\cos \hat{\psi} \sin \hat{\phi} & \cos \hat{\phi} \end{bmatrix} \begin{bmatrix} \dot{\hat{\phi}} \\ \dot{\hat{\theta}} \\ \dot{\hat{\psi}} \end{bmatrix} \end{aligned} \quad (2.5)$$

Since we desire to know the gimbal angle command signals which provide prescribed cab rotation rates we can invert the 3×3 matrix of (2.5) to obtain

$$\begin{pmatrix} \dot{\hat{\phi}} \\ \dot{\hat{\theta}} \\ \dot{\hat{\psi}} \end{pmatrix} = \begin{bmatrix} 1 & -\tan \hat{\psi} \cos \hat{\phi} & \tan \hat{\psi} \sin \hat{\phi} \\ 0 & \cos \hat{\phi} / \cos \hat{\psi} & -\sin \hat{\phi} / \cos \hat{\psi} \\ 0 & \sin \hat{\phi} & \cos \hat{\phi} \end{bmatrix} \begin{pmatrix} \hat{p} \\ \hat{q} \\ \hat{r} \end{pmatrix} \quad (2.6)$$

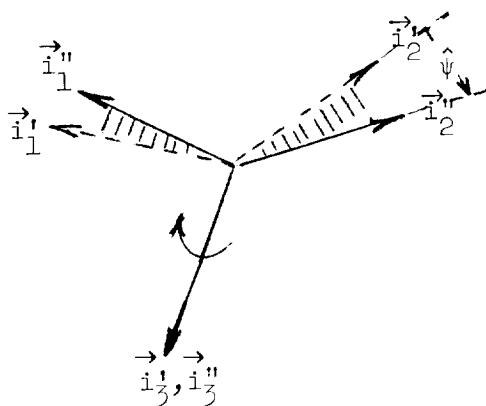
$\triangleq M \hat{\omega}_c$



(a) Pitching about \vec{i}_2 axis

$$T_{i'/i} = \begin{bmatrix} \cos \hat{\theta} & 0 & -\sin \hat{\theta} \\ 0 & 1 & 0 \\ \sin \hat{\theta} & 0 & \cos \hat{\theta} \end{bmatrix}$$

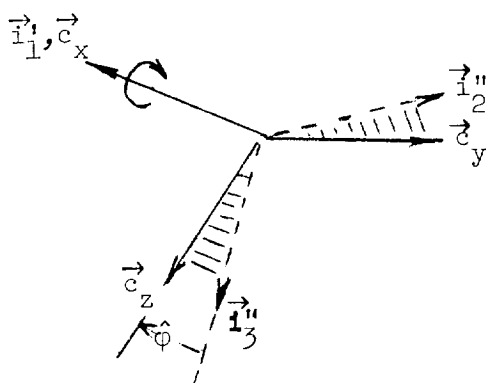
$$\hat{\omega}_{i'} = \begin{bmatrix} 0 \\ \dot{\hat{\theta}} \\ 0 \end{bmatrix} = \begin{matrix} \text{body rate due to pitch} \\ \text{gimbal rate in } i' \text{ frame} \end{matrix}$$



(b) Yawing about \vec{i}_3' axis

$$T_{i''/i'} = \begin{bmatrix} \cos \hat{\psi} & \sin \hat{\psi} & 0 \\ -\sin \hat{\psi} & \cos \hat{\psi} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\hat{\omega}_{i''} = \begin{bmatrix} 0 \\ 0 \\ \dot{\hat{\psi}} \end{bmatrix} = \begin{matrix} \text{body rate due to yaw} \\ \text{gimbal rate in } i'' \text{ frame} \end{matrix}$$



(c) Rolling about \vec{i}_1'' axis

$$T_{c/i''} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \hat{\phi} & \sin \hat{\phi} \\ 0 & -\sin \hat{\phi} & \cos \hat{\phi} \end{bmatrix}$$

$$\hat{\omega}_c = \begin{bmatrix} \dot{\hat{\phi}} \\ 0 \\ 0 \end{bmatrix} = \begin{matrix} \text{body rate due to roll} \\ \text{gimbal rate in cab frame} \end{matrix}$$

Figure 2.2. Rotation Sequence, Intermediate Transformations and Rates

As an example suppose we wished to have cab rotation rates follow a prescribed time history $\omega_c(t)$. If we place $\omega_c(t)$ in place of $\hat{\omega}_c$ in equation (2.6) we can compute the gimbal angle rates. An integration of these rates will in turn provide the gimbal angle command signals.

The transformation from inertial to cab axis is the product of the three transformations shown in Figure 2.2.

$$T_{c/i} = T_{c/i''} T_{i''/i'} T_{i'/i}$$

$$= \begin{bmatrix} (\cos\hat{\psi}\cos\hat{\theta}) & (\sin\hat{\psi}) & (-\cos\hat{\psi}\sin\hat{\theta}) \\ (-\cos\hat{\phi}\sin\hat{\psi}\cos\hat{\theta} + \sin\hat{\phi}\sin\hat{\theta}) & (\cos\hat{\phi}\cos\hat{\psi}) & (\cos\hat{\phi}\sin\hat{\psi}\sin\hat{\theta} + \sin\hat{\phi}\cos\hat{\theta}) \\ (\cos\hat{\theta}\sin\hat{\psi}\sin\hat{\phi} + \sin\hat{\theta}\cos\hat{\phi}) & (-\sin\hat{\phi}\cos\hat{\psi}) & (-\sin\hat{\phi}\sin\hat{\psi}\sin\hat{\theta} + \cos\hat{\phi}\cos\hat{\theta}) \end{bmatrix} \quad (2.7)$$

Since the transformation given by (2.7) is orthogonal the transformation from cab to inertial frames is

$$T_{i/c} = T_{c/i}^T \quad (2.8)$$

where the superscript $()^T$ means the transpose.

In the sequel it is assumed that the servo mechanisms of the motion generator can follow the position signals, \hat{r}_i , and the gimbal angle commands, $[\hat{\phi}, \hat{\theta}, \hat{\psi}]$, with negligible error. Actually the servo drive system lags must be compensated for with lead as discussed in Appendix A in order for this error to be small. Since this lead is used, the specific force and angular rates determined from previous equations are assumed to be those presented to the pilot in the cab of the motion generator.

2.3 Summary of Pilot Perceptions and Motion Generation. - A pilot in the simulator cab is assumed to deduce his attitude, position and velocity from the visual displays in the cab. The cab itself may take on arbitrary values of these quantities within the constraints of the motion drive mechanism. The pilot's only fixed reference is the cab around him. Hence, the specific forces resulting from motion of a simulated aircraft

should be presented to the pilot in the cab so that it has the same direction with respect to the cab as the true specific force would have with respect to the cockpit of the aircraft. The specific force vector at the cockpit of the simulated aircraft can be represented as

$$f_c = T_{c/i}(\theta, \phi, \psi)(\ddot{r}_i - g_i) \quad (2.9)$$

where

$T_{c/i}(\theta, \phi, \psi)$ = the orthogonal transformation from inertial space to the reference frame fixed in the cockpit.
 \ddot{r}_i = the acceleration of the cockpit with respect to inertial space (note that this includes acceleration at the aircraft cg + acceleration due to rotations of the aircraft and displacement of cockpit from the cg).
 g_i = gravity vector in the inertial reference frame acting at the cockpit.

Similarly, the specific force felt by the pilot in the cab can be represented as

$$\hat{f}_c = T_{c/i}(\hat{\theta}, \hat{\phi}, \hat{\psi})(\ddot{\hat{r}}_i - \hat{g}_i) \quad (2.10)$$

where

$T_{c/i}(\hat{\theta}, \hat{\phi}, \hat{\psi})$ = the orthogonal transformation from the pit to the cab frame
 $\ddot{\hat{r}}_i$ = acceleration of the cab in pit reference (for the All-Axis Motion Generator the pilot is located at the center of rotation (approximately))
 \hat{g}_i = the gravity vector in the pit reference

Quantitatively, it is assumed that when $f_c = \hat{f}_c$ the simulator is giving perfect specific force cues. Qualitatively, it would be desirable to have any component of \hat{f}_c sensed by a pilot to be related to what a pilot actually would feel in that channel. From his point of view, it would be particularly unappealing to have a simulator motion

which would result in a laterally felt specific force with respect to an aircraft actually producing vertically sensed specific forces with respect to the cab.

Just as with specific force, the important angular rate quantities to match are

$$\hat{\omega}_c = \omega_c \quad (2.11)$$

where again it would be desirable to at least have each channel in good relation with motion which would affect that channel.

Figure 2.3 is a schematic of the motion generator command logic from what has been discussed thus far. From the computer simulation of the aircraft we obtained the desired specific force vector, f_c , and angular rate vector, ω_c . These quantities act at the cockpit location of the aircraft and are specified in a reference frame fixed to the cockpit with an origin at the pilot's station. The washout logic modifies the quantities in such a manner that the commanded specific force, \hat{f}_c , and body rate, $\hat{\omega}_c$,

- 1) bear a reasonable resemblance to the real quantities such that a pilot in the cab considers the motion realistic
- and
- 2) do not cause the motion generator to reach any of its design limits which cause a hard cut off.

As we will see in subsequent sections the design of this washout logic is not a straightforward problem. The next section illustrates some of the difficulties imposed by the constraints.

2.4 Influence of Motion Generator Constraints. - The previous sections illustrated how mathematically one may derive command signals for the motion generator which prescribe the specific force and rotation rates of the cab. The motion generator has constraints which preclude presenting totally arbitrary values of these quantities. This section describes the constraints and presents a tutorial example of their potentially deleterious effects on the pilot sensed quantities.

The constraints in the translational drives may be approximated by

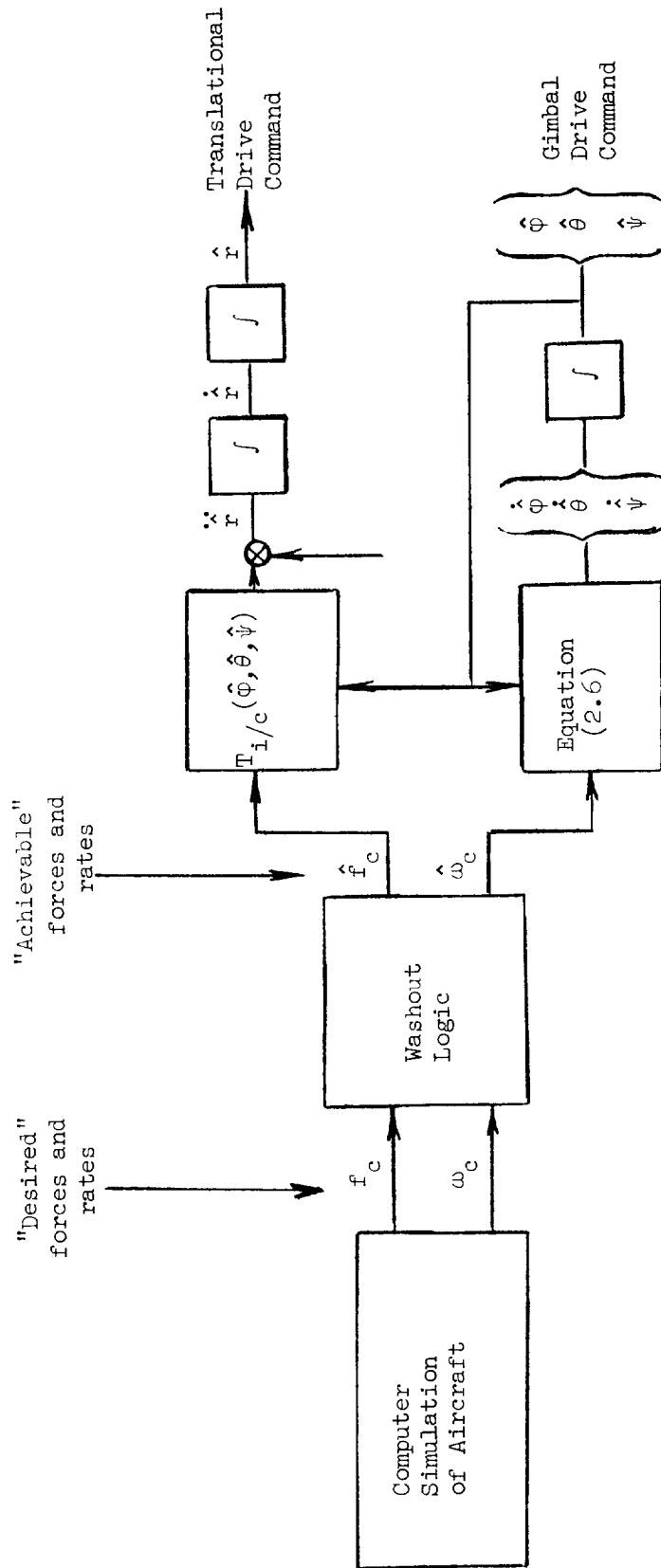


Figure 2.3. Schematic of Motion Generator Command Logic

limits on the magnitudes of the components of position, velocity, and acceleration in the inertial (pit) frame. This frame has its axis parallel to the longitudinal, lateral, and vertical drive tracks.

Define

$$\hat{\mathbf{r}} = \begin{pmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{pmatrix} ; \quad \dot{\hat{\mathbf{r}}} = \begin{pmatrix} \dot{\hat{x}} \\ \dot{\hat{y}} \\ \dot{\hat{z}} \end{pmatrix} ; \quad \ddot{\hat{\mathbf{r}}} = \begin{pmatrix} \ddot{\hat{x}} \\ \ddot{\hat{y}} \\ \ddot{\hat{z}} \end{pmatrix} \quad (2.12)$$

Then the components are bounded by inequalities like

$$|\hat{y}| \leq 9 \text{ ft} \quad |\dot{\hat{y}}| \leq 14 \text{ ft/sec} \quad |\ddot{\hat{y}}| \leq 7 \text{ ft/sec}^2 \quad (2.13)$$

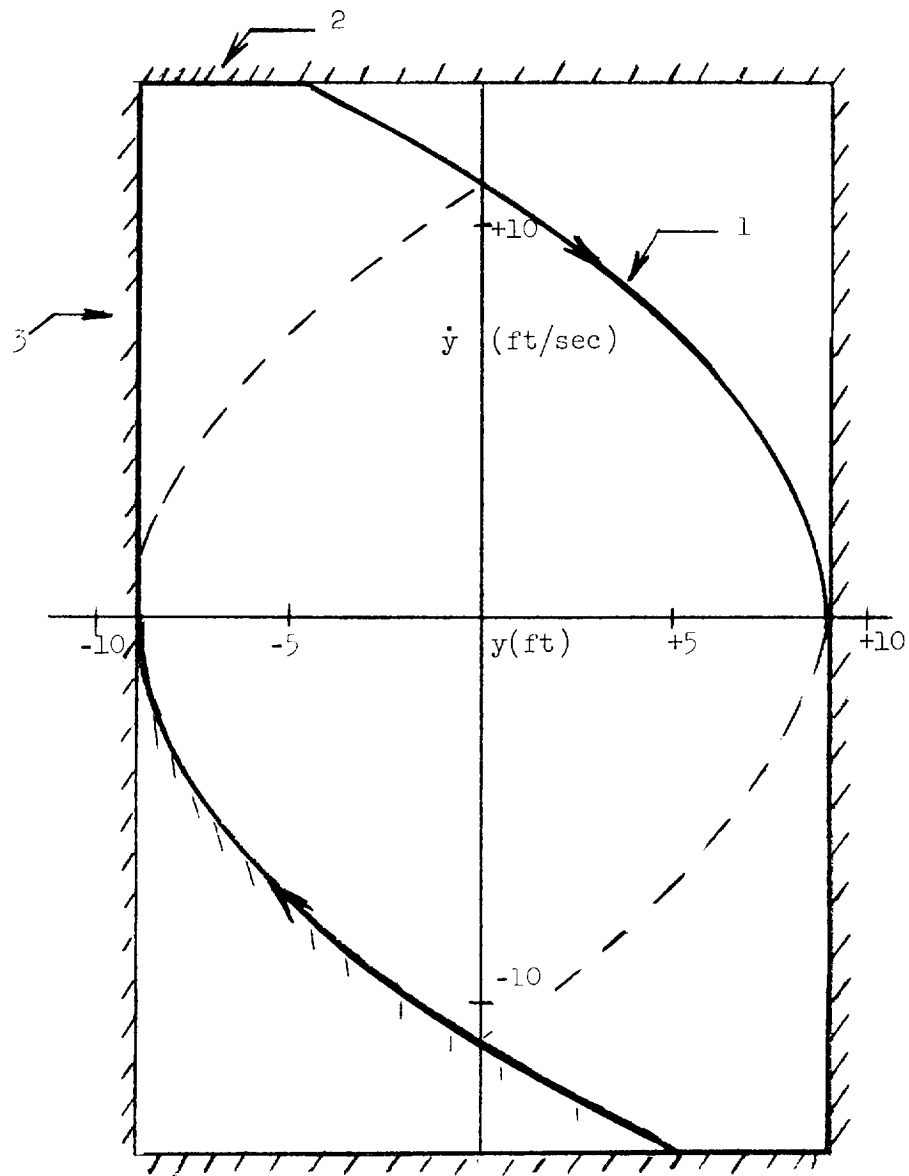
Similar limits exist for the other components (see Appendix A). The gimbal angles $\hat{\phi}$, $\hat{\theta}$, and $\hat{\psi}$ also correspond to individual rotation drives. The constraints on these drives may be specified in a similar manner.

$$|\hat{\psi}| \leq 45^\circ; \quad |\dot{\hat{\psi}}| \leq 4.9 \text{ rad/sec}; \quad |\ddot{\hat{\psi}}| \leq 6 \text{ rad/sec}^2 \quad (2.14)$$

Constraints involving derivatives limit the region in the state space to values somewhat smaller than the first two relations of the type shown in (2.13) would imply. Physically this arises because certain allowable values of initial position and velocity imply that the cab is drifting towards a constraint boundary. The acceleration constraint precludes reducing the velocity to zero instantaneously. Hence the boundaries must enclose only that region where the acceleration capabilities can cause the cab to come to rest (zero velocity) at the position limits. Figure 2.4 illustrates this region for the lateral drive system.

In this figure, boundaries 2 and 3 are determined directly from equation (2.13). Boundary 1 is obtained by considering the maximum accelerations which can be used to offset the velocity the cab has at a given position. If the cab strays from the inner region enclosed by the heavy lines, it is committed to a hard cutoff.

It is instructive to consider the simulation problems associated with the constraints of equation (2.13) if only this channel were being used



- 1) velocity constraint imposed by acceleration and position limits
- 2) velocity constraint imposed by the drive system servos
- 3) position constraint on travel

Figure 2.4. Phase Plane Representation of Lateral Drive Constraints.

(no tilts, forward accelerations etc.) and the computer indicated a constant lateral force on the pilot for a long duration of time. Figure 2.5 depicts what would have to be done to simulate a lateral force of 2 ft/sec^2 if the simulator were started from $\hat{y}(0) = \dot{\hat{y}}(0) = 0$.

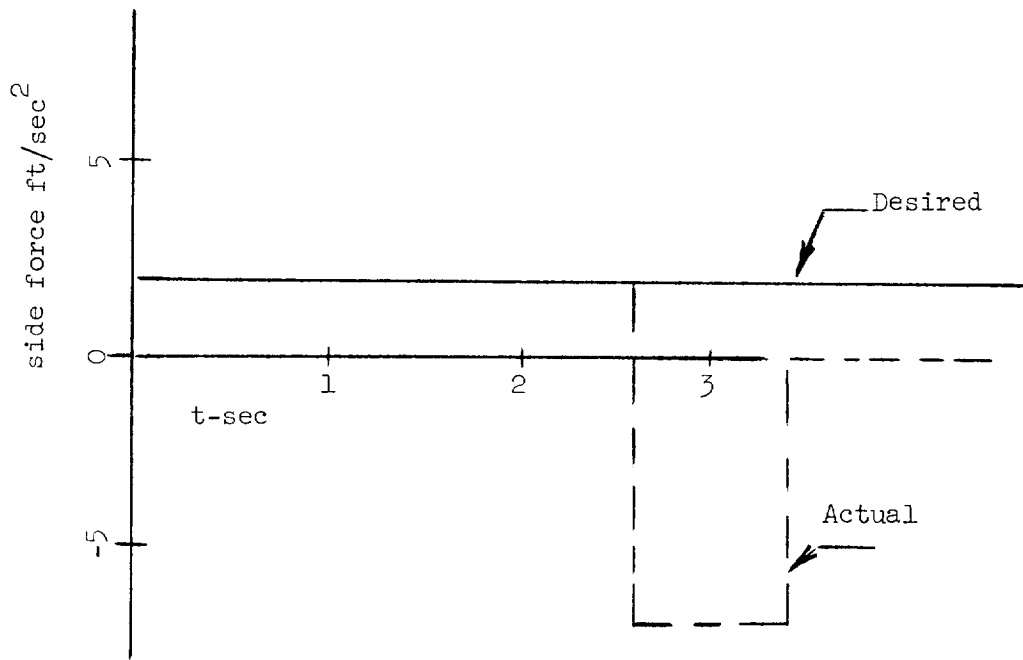


Figure 2.5. Effects of Constraints on Ability to Generate a Constant Lateral Force.

As illustrated we can apply an acceleration $\ddot{\hat{y}} = 2 \text{ ft/sec}^2$ for a period of only 2.65 seconds. At this time we must reverse the acceleration to $\ddot{\hat{y}} = -7 \text{ ft/sec}^2$ (the maximum possible) for approximately .754 seconds in order to stop the cab at the 9 ft position limit. This abrupt departure from the desired acceleration (or specific force) history is very undesirable. This simple example illustrates the difficulty in presenting proper forces when faced with the relatively small position boundary of equation (2.13). Although alternative schemes involving less severe excursions from the desired force history will be discussed later it is clear that some anomalous motion must always be tolerated in such a problem.

SECTION 3

WASHOUT LOGIC DESIGN

The design of washout logic begins with a knowledge of the motion generator capabilities and of the constraints which are likely to be violated. Logic is then designed to modify the "desired" forces and/or rates such that the command signals stay within the attainable regions of the motion generator. We would like this logic to also provide the subject pilot with a realistic "feel" of flying the actual aircraft.

Traditionally, washout logic is comprised of linear constant parameter networks whose overall configuration is selected to constrain the motion drive signals in an appropriate manner. The parameters of these networks are then chosen empirically so as to provide as acceptable a motion as possible while remaining within the motion generator constraint limits for the "worst case". This section describes the traditional logic which has been successfully used for motion generators with one to three degrees of freedom.

3.1 Washout for a Translational Channel. - The simulated aircraft can go through very large position and velocity excursions compared to the constraint boundaries of any ground based motion generator. Consequently the acceleration must be modified in some manner to avoid hard cutoff limiting. Traditionally, this modification has been accomplished by linear filters appropriately selected such that the position is bounded for a constant acceleration input. These high pass filters remove slowly varying accelerations from the command signals while retaining the rapidly varying terms whose integrals do not cause large position (or velocity) excursions. For example, consider a problem where the simulated aircraft is flying straight and level and the forward velocity is being changed by throttle adjustments. For this case, the inertial and cab references are aligned. Since g acts vertically, we can write

$$f_{cl} = \ddot{r}_{cl} = f_{il} = \ddot{r}_{il} \quad (3.1)$$

The specific force signal of (3.1) is fed through a high-pass, second-order filter and then integrated twice as illustrated in Figure 3.1

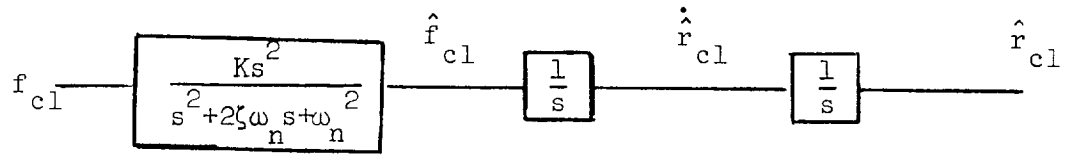


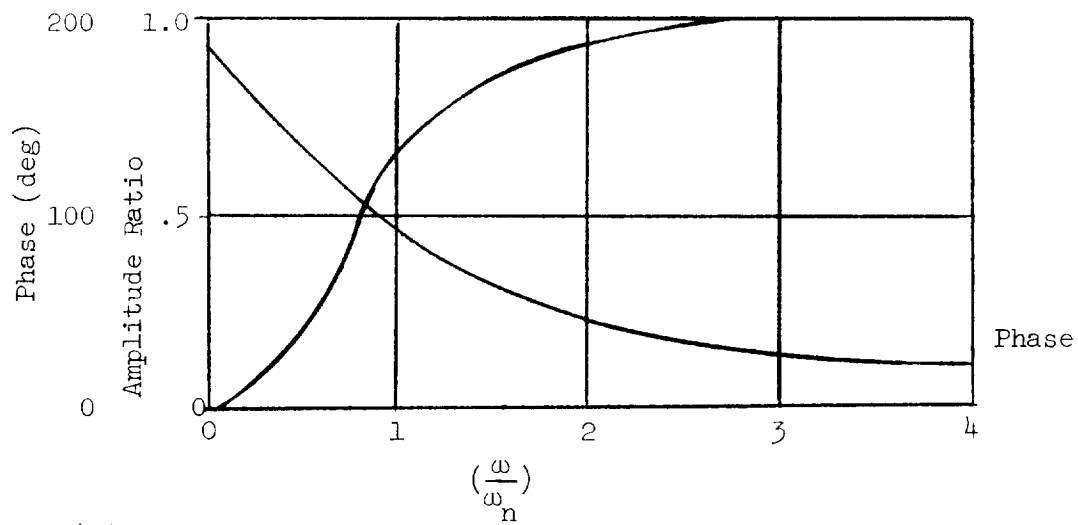
Figure 3.1. Washout Filter for a Translational Channel

One should note that this is the simplest form of a high pass filter which will bound \hat{r}_{cl} (if zero initial conditions on all states are selected). This bounding results from the fact that f_{cl} is bounded and so long as the network is stable and started from zero initial conditions then \hat{r}_{cl} is bounded. In the steady state we note that \hat{r}_{cl} is proportional to f_{cl} . This second-order filter then gives a cab displacement proportional to specific force (or acceleration) command for the low-frequency signals. Since the denominator is the same order as the numerator, very-high-frequency forces give cab accelerations.

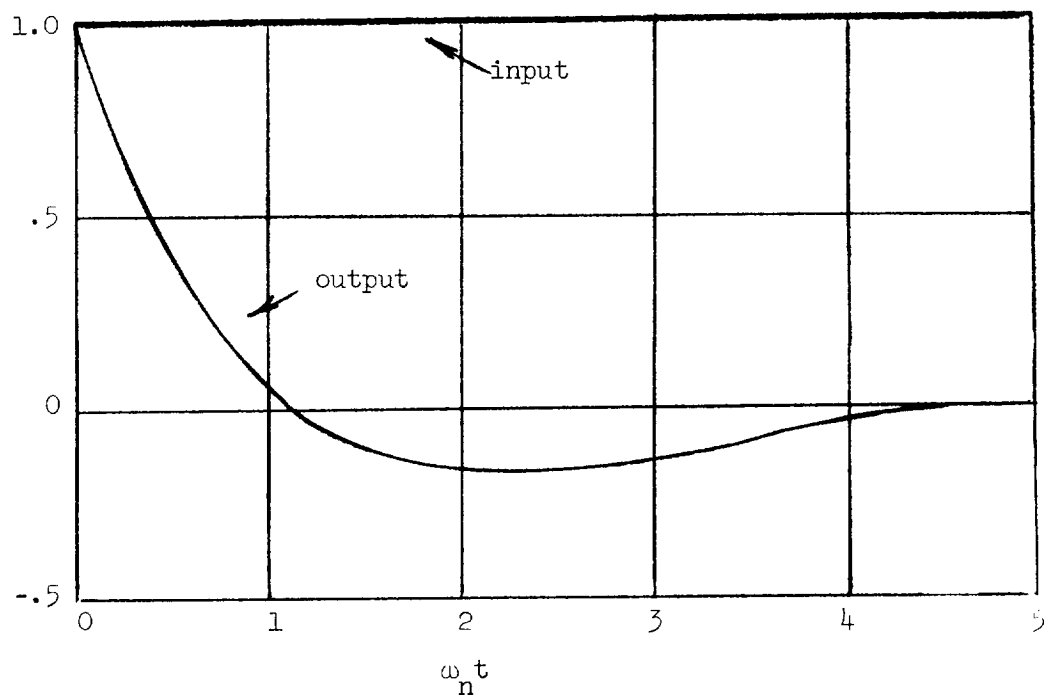
If we had selected only a single zero in the numerator of the filter transfer function then of course the cab displacement would grow indefinitely (until hard cut off) for a constant input force. If the zero in the numerator were higher than second order then the cab would restore to zero position for a constant force input.

The frequency and transient response characteristics of the second-order filter of Figure 3.1 are illustrated in Figure 3.2 for $K = 1$. The damping ratio was selected at the numerical value $\zeta = 0.75$ for illustrative purposes. In order to interpret these graphs, we need to choose a value of ω_n . It can be noted from Figure 3.1 that the steady state position for a constant desired acceleration, f_{cl} , is (assuming zero initial conditions)

$$\hat{r}_{cl} = \frac{K f_{cl}}{\omega_n^2}$$



(a) Frequency response for linear washout filter.



(b) Unit step response for linear washout filter.

Figure 3.2. Frequency-and Step-Responses for Translational-Channel Washout Filter.

If we assume a constant desired acceleration of 7 ft/sec^2 then to stay within the 9 foot position limits of the All-Axis Generator (see Appendix A) ω_n must be about

$$\omega_n = \sqrt{7/9} = .882 \text{ rad/sec}$$

From Figure 3.2a, it can be seen that if ω/ω_n is larger than about 2, the amplitude response is nearly constant. This ratio, $\omega/\omega_n = 2$, corresponds to $\omega = 1.76 \text{ rad/sec}$ or a frequency of 0.38 Hz . The phase lead at this frequency is still high (approximately 45°). In a pilot control problem the phasing of the signal is also very important. From Figure 3.2a it is seen that the frequency must be greater than about 1 Hz before the motions are reproduced with reasonable fidelity.

The step-response time history shown in Figure 3.2b illustrates the output of the high-pass filter for a step input. As noted the output acceleration (and sensed force) reverses sign to stop the cab. This reversal occurs when $\omega_n t$ is approximately 1.2

In addition to high-pass filtering, force scaling may also be used. For example, if a scaling factor of $K = 1/4$ is used, then ω_n can be reduced by a factor of $1/2$. Such scaling allows the preservation of correct direction at lower frequencies but with less than true amplitude.

In the vertical channel a candidate circuit is illustrated in Figure 3.3.

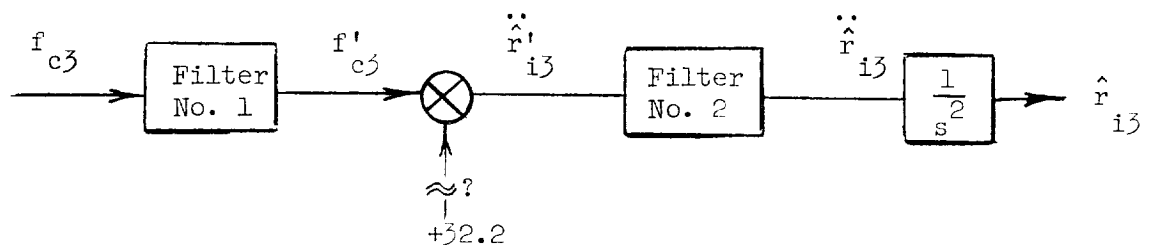


Figure 3.3. Washout Circuits for the Vertical Channel.

With this channel we begin to notice a difficulty which is significant

in all channels of a multi-degree-of-freedom simulator. That is, where should the signals be filtered? If the first filter is chosen to be of high pass type, then the approximately $1g$ normal force on a trimmed aircraft will be attenuated so that, in the steady state f'_{c3} will be about zero and the cab will be driven by the $1g$ input term. Hence a high pass filter at point 1, would require the removal of the $1g$ input. Introducing a high pass filter at the second point is actually feasible in the single channel case but will present coupling difficulties in the multichannel case.

3.2 Washout for a Rotational Channel. - With the possible exception of stunt flying (barrel rolls, spins, etc.), the pitch and roll attitudes are usually constrained in the real or simulated aircraft. Yaw is not constrained since steady turns are part of normal flying. Euler angle rates for all cases are constrained. Hence, for many normal problems the attitude cues could be exactly represented with the gimbal angle capability of the All-Axis Motion Generator. However, it is impossible to give attitude commands (with the exception of pure yaw with pitch and roll angles zero) without also affecting specific force on the pilot. Furthermore, in most flight situations the specific force on a pilot, relative to the cab, is approximately normal to his seat. We note that when $\hat{\theta}$ and $\hat{\phi}$ are zero, substitution of the appropriate terms into equation (2.10) shows that the specific force will in fact be normal to the seat (i.e., will be along the \hat{f}_{c3} direction only) with a value of $1g$ if $\ddot{r}_1 = 0$.

Suppose that only a roll rotation motion is available in a simulator and that we wish to give a pilot a sense of rotation cues, assuming that strictly normal specific force cues are desirable. The linear network of Figure 3.4 can then be used to yield the

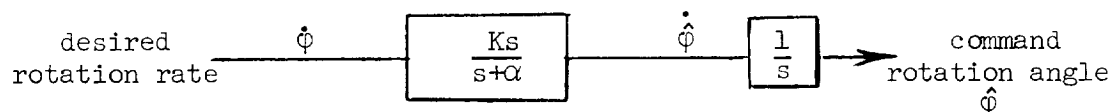


Figure 3.4. Washout Filter for a Rotational Channel.

desirable property that high frequency rates are followed. Furthermore, when the aircraft rate $\dot{\phi}$ goes to zero, the cab roll attitude, $\hat{\phi}$, returns to zero. The frequency and time response characteristics of this filter are depicted in Figure 3.5 for $K = 1$. Note that there is a trade made here between anomalous rates used to restore the cab and the sense of anomalous specific force in the longitudinal and vertical direction which would otherwise result.

In particular, in the one-degree-of-freedom example

$$\hat{f}_c = \begin{Bmatrix} 0 \\ -32.2 \sin \hat{\phi} \\ -32.2 \cos \hat{\phi} \end{Bmatrix}$$

which, for small $\hat{\phi}$ is approximated by

$$\hat{f}_c \approx \begin{Bmatrix} 0 \\ -32.2 \hat{\phi} \\ -32.2 \end{Bmatrix}$$

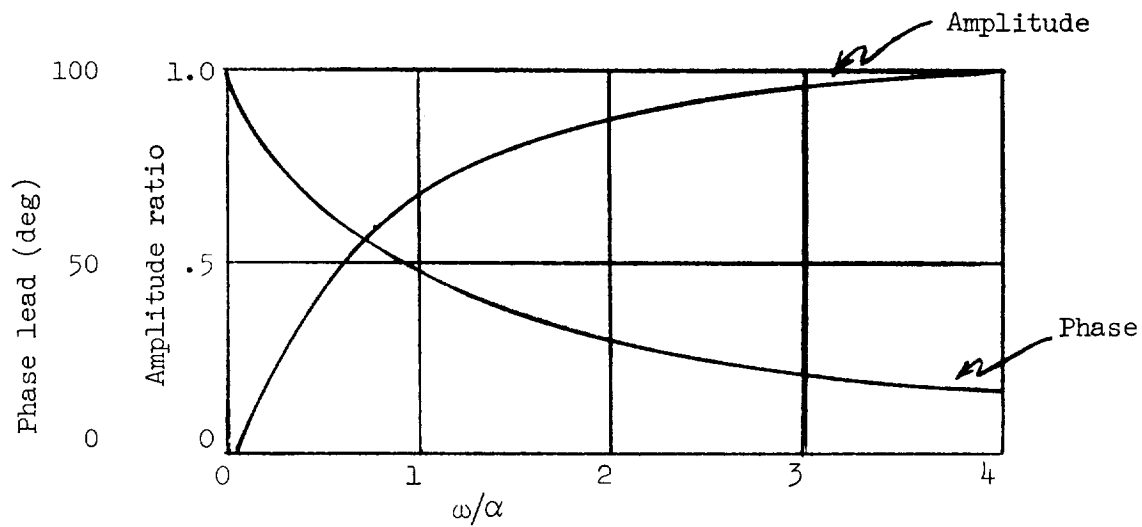
So if we are trying to simulate coordinated flight conditions, say a coordinated turn, the second component $\hat{f}_{c2} = -32.2 \hat{\phi}$ is in complete error for $\hat{\phi}$ other than zero.

As an example let the input pulse amplitude be .2 rad/sec and the reciprocal time constant α , equal 0.5. Then with reference to Figure 3.5b the maximum undesired specific force, f_{c2} , occurs at $t \approx 4$ seconds and has a value of

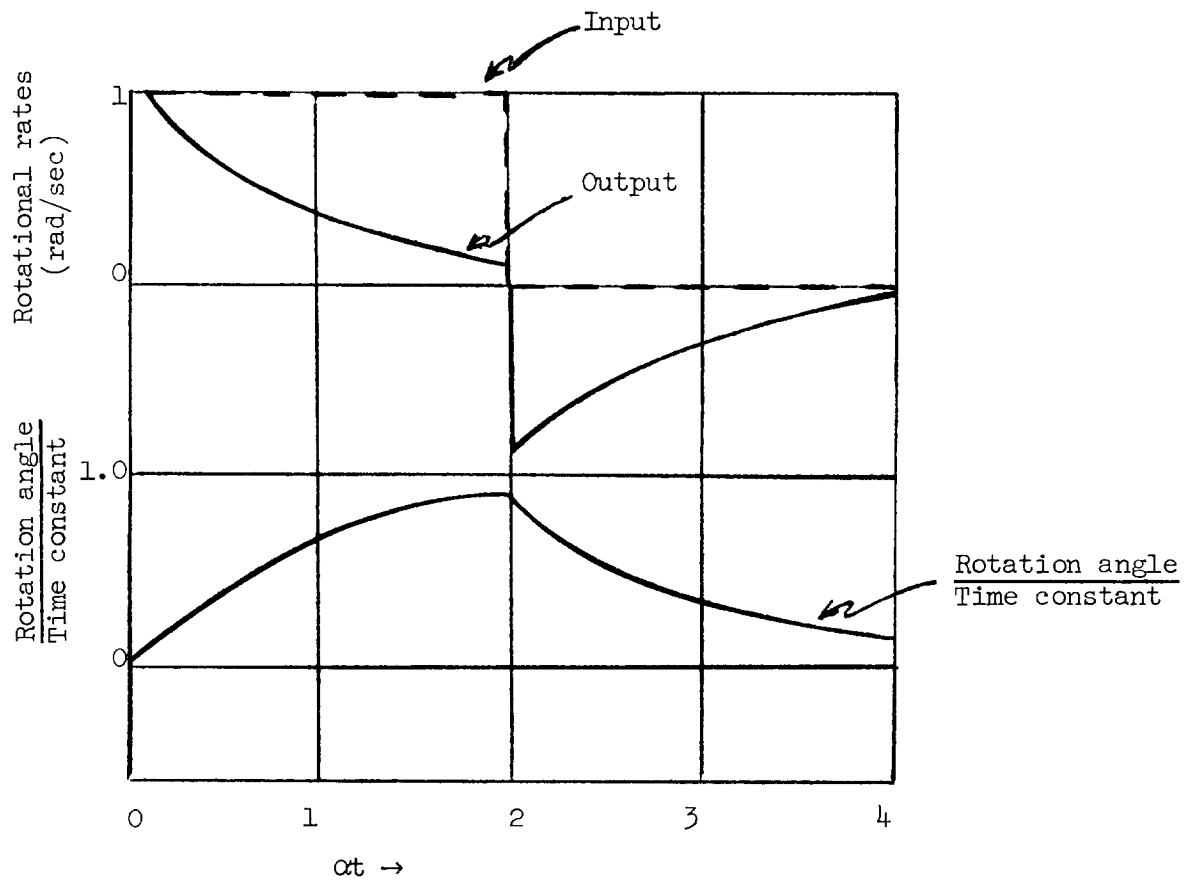
$$\hat{f}_{c2} = -(.2)(2)(.9)(32.2) = -11.6 \text{ ft/sec}^2$$

This undesired specific force reduces with time since the cab gradually restores to an upright position.

The removal of the undesired force is accomplished by the added anomalous rotation rate (difference between input and output of Figure 3.5). We see therefore that at best only a compromise can be obtained since in attempting to remove one anomalous "cue" we have introduced a second anomalous motion. One may also reduce the gain in the rotational channel. This permits a reduction in anomalous forces as well as anomalous rotation motions at the penalty of a reduced amplitude.



(a) Frequency response for rotational washout filter.



(b) Unit pulse responses for rotational washout filter.

Figure 3.5. Frequency and Pulse Responses for a Rotational Channel Washout Filter.

3.3 Utilizing Rotations to Obtain Specific Force Cues; Residual Tilts. -

The foregoing discussion indicates that rotation angles (tilts) alter the specific force on a pilot. This effect is often utilized to simulate specific forces in the lateral and longitudinal directions. A force sensation arising from a tilt sensation can be held indefinitely, unlike specific force sensations arising from translational acceleration. Consider, for example, a simulator restricted to pitch and roll motion, but no translation ($\hat{\mathbf{r}}_i = 0$). Then equation (2.11) is written

$$\hat{\mathbf{f}}_c = \begin{Bmatrix} \hat{f}_{c1} \\ \hat{f}_{c2} \\ \hat{f}_{c3} \end{Bmatrix} = -T_{c/i}(\hat{\theta}, \hat{\phi}, \hat{\psi}) \cdot \mathbf{g}_i \quad (3.2)$$

We note immediately that since T is an orthonormal transformation matrix that

$$|\hat{\mathbf{f}}_c| = |\mathbf{g}_i| = 32.2 \text{ ft/sec}^2 ,$$

that is, the magnitude of the specific force obtained by tilting is independent of the tilt angles. Since a trimmed aircraft usually has an approximately 1g normal component we are generally constrained to small tilt angles or this normal component would become unrealistically small. For small tilt angles, the transformation $T_{c/i}$ can be written

$$\begin{aligned} T_{c/i}(\hat{\phi}, \hat{\theta}, \hat{\psi}) &\approx \begin{bmatrix} 1 & \hat{\psi} & -\hat{\theta} \\ -\hat{\psi} & 1 & \hat{\phi} \\ \hat{\theta} & -\hat{\phi} & 1 \end{bmatrix} \\ &= [I] - [\hat{\rho} \times] \end{aligned} \quad (3.3)$$

where I is the 3×3 identity matrix and the last term defines a anti-symmetric cross product matrix associated with the vector

$$\hat{\rho} \triangleq \begin{Bmatrix} \hat{\phi} \\ \hat{\theta} \\ \hat{\psi} \end{Bmatrix} \quad (3.4)$$

$$[\hat{\rho}x] = \begin{bmatrix} 0 & -\hat{\psi} & \hat{\theta} \\ \hat{\psi} & 0 & -\hat{\phi} \\ -\hat{\theta} & \hat{\phi} & 0 \end{bmatrix} \quad (3.5)$$

Hence for small angles

$$\hat{f}_c = -T_{c/i}(\hat{\phi}, \hat{\theta}, \hat{\psi})g_i = \begin{bmatrix} 32.2 \hat{\theta} \\ -32.2 \hat{\phi} \\ -32.2 \end{bmatrix} \quad (3.6)$$

In the context of giving just rotation cues, the first two components of equation (3.6) represent anomalous forces. However, we see that the logic of Figure 3.6 can be used to generate specific force cues.

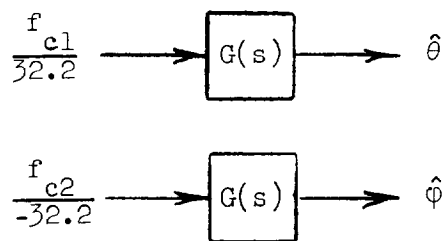


Figure 3.6. Generation of Tilt Commands to Obtain Specific Force Cues.

In this figure a linear network $G(s)$ is included to suppress high frequency components of the input forces. This lag network reduces rolling and pitching sensations which result from rapidly acting forces. Traditionally, the rotations illustrated in Figure 3.6 are added to the rotation commands from circuits like Figure 3.4. Such commands in a 2 degree of freedom simulator give both force and rotation sensations to the pilot.

3.4 Coupling Translational and Rotational Channels. — When a horizontal motion drive and rotation drive are both available (e.g., a cab with pitch and longitudinal motion drives) then the drives can be coupled to

improve the specific force sensations. Figure 3.7 illustrates how this coupling can be accomplished

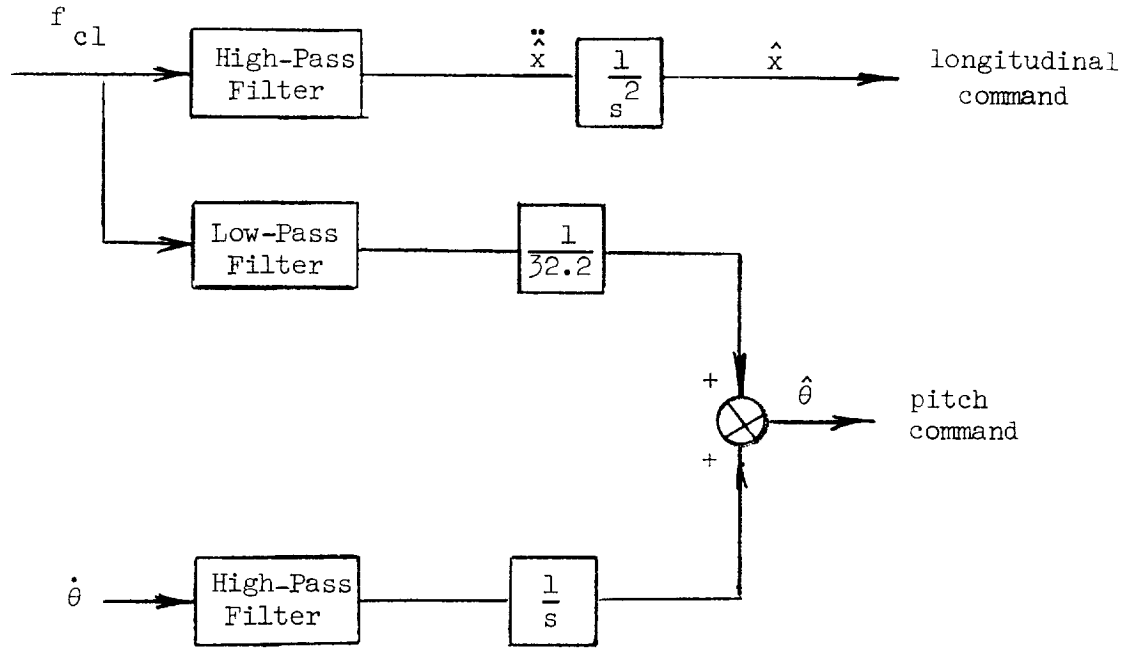


Figure 3.7. Coupling of Translational and Rotational Channels.

As is noted, the desired force signal, f_{cl} , is split into high- and low-frequency components by the two filters. The longitudinal command generates the high-frequency components of the specific force while residual tilts provide the low-frequency components.

The rotational cues given to the pilot consist of the high-frequency components of the desired rotations plus the residual tilt rotations.

SECTION 4

MULTI-DEGREE OF FREEDOM WASHOUT CIRCUITS

The procedure used to generalize the washout circuit design problem to the multi-degree of freedom case will be considered in three steps. First, we try to provide the specific force cues with the translation drive channels. Second, we try to obtain good rotational acceleration cues using the rotational channels. Third, compromises between the channels are made so that rotations, for example, can be used to create side force cues using coordinated washout logic.

4.1 Washout Circuits for Translation Drive Channels. - The design of washout circuits for several translational channels adds to previously discussed difficulties the problem of coupling between channels. This arises because motion constraints involve physical quantities expressed in an inertial (pit) coordinate frame, whereas specific force cues are sensed by a pilot in a cab coordinate frame. We recall that if an aircraft pilot feels a specific force (in his cab frame) of f_c , we would like the simulation cab pilot to feel

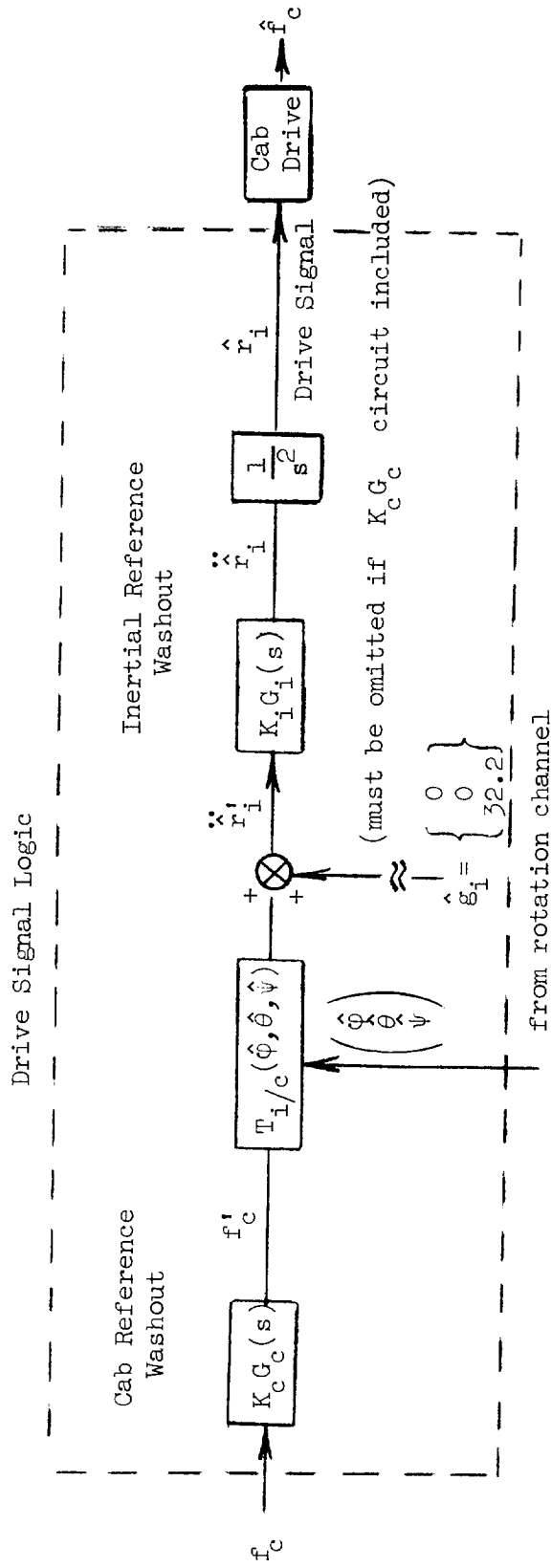
$$f_{c1} \sim \hat{f}_{c1}$$

$$f_{c2} \sim \hat{f}_{c2}$$

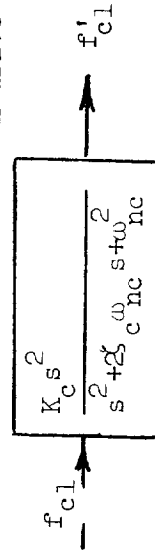
$$f_{c3} \sim \hat{f}_{c3}$$

that is, the various components should be closely related. We specifically wish to avoid coupling between channels. For example, we do not want an aircraft specific force corresponding to f_{c2} to yield changes in \hat{f}_{c1} .

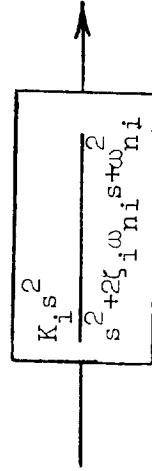
Figure 4.1a presents the logic necessary to obtain specific forces in the cab frame as per the explanation in Section 2 with the addition of two linear networks to serve the limiting functions discussed in Section 3. Subsequent paragraphs discuss the consequences of utilizing this logic by considering several cases.



(a) General form of translation drive system.



(b) Cab reference washout. Each channel has this form. One can choose different parameters for each channel.



(c) Inertial reference washout. Same comments as (b) above.

Figure 4.1. Alternate Washout Circuits for Translational Drive System.

No Washout Used. In flight tasks where no limits are likely to be exceeded, the washout networks can be eliminated by setting

$$K_i = K_c = 1.0 \quad (4.1)$$

$$\omega_{ni} = \omega_{nc} = 0$$

In this case it is readily seen that

$$\ddot{\hat{r}}_i = T_{i/c}(\hat{\theta}, \hat{\phi}, \hat{\psi}) f_c + \hat{g}_i \quad (4.2)$$

so that

$$\begin{aligned} \hat{f}_c &= T_{c/i}(\hat{\theta}, \hat{\phi}, \hat{\psi}) \{ T_{i/c}(\hat{\theta}, \hat{\phi}, \hat{\psi}) f_c + \hat{g}_i - \hat{g}_i \} \\ &= f_c \end{aligned} \quad (4.3)$$

which gives perfect specific force reproduction.

Cab Reference Washout. Direct modification of signals given in a cab frame is referred to as "cab reference" washout. This circuit may be analyzed by removing the inertial reference washout (i.e., set $K_i = 1.0$ and $\omega_{ni} = 0$), and considering the types of anomalous motion introduced by such a network. The advantage of such a network is that it avoids coupling between channels. The disadvantages involve the introduction of anomalous attitude dependent specific force cues and the fact that limiting at this point is not always sufficient to guarantee limiting of the integrals of $\ddot{\hat{r}}_i$.

Since the circuit $G_c(s)$ is a high pass filter, it will attenuate any constant level terms in f_c . The specific force f_c however contains (in normal flight conditions) an approximate value of $-lg$. This term is usually canceled in large part by the \hat{g}_i input. Hence, a high pass cab reference filter requires the omission of the \hat{g}_i terms so the system does not see a large, constant driving term. From Figure 4.1a with the above restrictions

$$\ddot{\hat{r}}_i = T_{i/c}(\hat{\theta}, \hat{\phi}, \hat{\psi}) f'_c \quad (4.4)$$

Equation (4.4) illustrates that simply choosing a network which bounds f'_c and its integrals is not sufficient to assure that the integral of $\ddot{\hat{r}}_c$ are bounded. This results since $\ddot{\hat{r}}_i$ depends on both f'_c and the attitude time histories $\hat{\theta}$, $\hat{\phi}$ and $\hat{\psi}$.

To show this we define the signal changes due to cab reference washout as

$$\epsilon(t) = f'_c - f_c \quad (4.5)$$

Using equations 2.10, 4.4, and 4.5 we can solve for f_c to obtain

$$\hat{f}_c = f_c + \epsilon - T_{c/i}(\hat{\theta}, \hat{\phi}, \hat{\psi})\hat{g}_i \quad (4.6)$$

The two rightmost terms of equation 4.6 constitute anomalies in simulator specific force cues for this circuit. In a positive note, ϵ errors don't cross couple into other channels. On a negative note, in addition to some magnitude errors in the third channel (the up-down direction in the cab) attitude dependent specific forces due to tilting occur in the lateral and forward direction relative to the simulator cab.

Inertial Reference Washout. Modification of signals directly related to the inertially coordinatized quantities representing drive signals will be called inertial reference washout. To analyze this we set $K_c = 1$ and $\omega_{nc} = 0$ and consider the effect of the remaining network. Since the drive signals are directly modified, the rationale applied to single channel networks in Section 3 can be used to demonstrate that this logic can be chosen so that commands stay within the motion limits. With reference to figure (4.1) we can write the acceleration $\ddot{\hat{r}}$ in the following form.

$$\ddot{\hat{r}}_i = K_i \ddot{\hat{r}}'_i - \omega_{ni}^2 \iint \ddot{\hat{r}}_i - 2\zeta\omega_{ni} \int \ddot{\hat{r}}_i \quad (4.7)$$

This equation shows that the acceleration in any channel in the inertial frame is dependent on the past history of the acceleration. Substituting (4.7) into (2.10) and using $\ddot{\hat{r}}'_i = T_{i/c}f_c + \hat{g}_i$ we find

$$\hat{f}_c = K_i f_c + (K_i - 1)g_c + T_{c/i} \{ -\omega_{ni}^2 \iint \ddot{\hat{r}}_i - 2\zeta\omega_{ni} \int \ddot{\hat{r}} \} \quad (4.8)$$

From Equation (4.8) we see that inertial reference washout causes a pilot to feel 1) a scaled version of the aircraft specific force, 2) if $K_i \neq 1$, a force from tilts, and 3) a force involving past histories of inertial acceleration multiplied by the transformations matrix $T_{c/i}$. The third term can cause coupling effects if $T_{c/i}$ is changing.

An Alternative Translation Washout Scheme. An interesting variation on the circuit shown in Figure 4.1 can be obtained utilizing the fact that a simulator is normally only capable of delivering small perturbations to the lg normal force due to gravity. The long-term (low-frequency) specific force is usually $\sim lg$ on a pilot in an aircraft. This leads to the following logic. Subtract the principle portion of the low frequency terms of f_c before a cab reference washout filter, and add it back in at the output end, thus permitting \hat{g}_i in Figure 4.1 to remain in the loop with cab reference washout. Such a scheme is shown in Figure 4.2, where, for simplicity, only cab reference scaling is considered ($\omega_{nc} = 0$).

With this arrangement f'_c is seen to be

$$f'_c = K_c f_c + (-1 + K_c) \hat{g}_i \quad (4.9)$$

so that

$$\hat{f}_c = K_c f_c + (-1 + K_c) \hat{g}_i \quad (4.10)$$

From Equation (4.10) we see that the simulator pilot will feel the usual lg plus a scaled down version of the aircraft departure from that value. Furthermore, coupling is avoided since changes in a channel of f_c gives changes in the corresponding channel of \hat{f}_c .

Next, the ability of such a circuit to provide adequate limiting must be examined. The relevant differential equation is

$$\ddot{r}_i = T_{i/c} \{ K_c f_c + (K_c - 1) \hat{g}_i \} + \hat{g}_i \quad (4.11)$$

When the cab has no rotation so that $T_{i/c}$ is the identity matrix, this equation reduces to

$$\ddot{r}_i = K_c (f_c + \hat{g}_i) \quad (4.12)$$

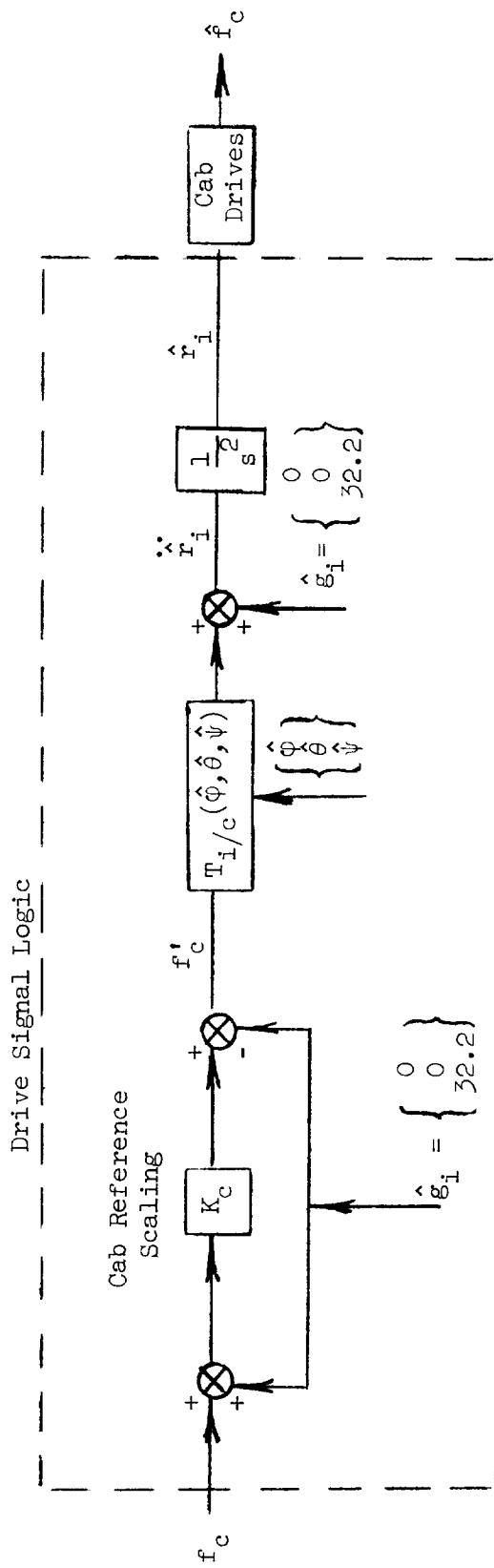


Figure 4.2. A Translational Drive System with Cab Reference Scaling

Hence, if the aircraft has bounded position and velocity, K_c can always be chosen small enough to provide adequate limiting since the integrals of $(f_c + \hat{g}_i)$ are bounded.

For any other cab attitude, however, the question of bounding with a K_c again becomes moot. For small angles (see Equation 3.3), Equation (4.11) becomes

$$\begin{aligned}\ddot{r}_i &= K_c T_{i/c} \{f_c + \hat{g}_i\} - T_{i/c} \hat{g}_i + \hat{g}_i \\ &\approx K_c T_{i/c} \{f_c + \hat{g}_i\} - \rho \times \hat{g}_i\end{aligned}\quad (4.13)$$

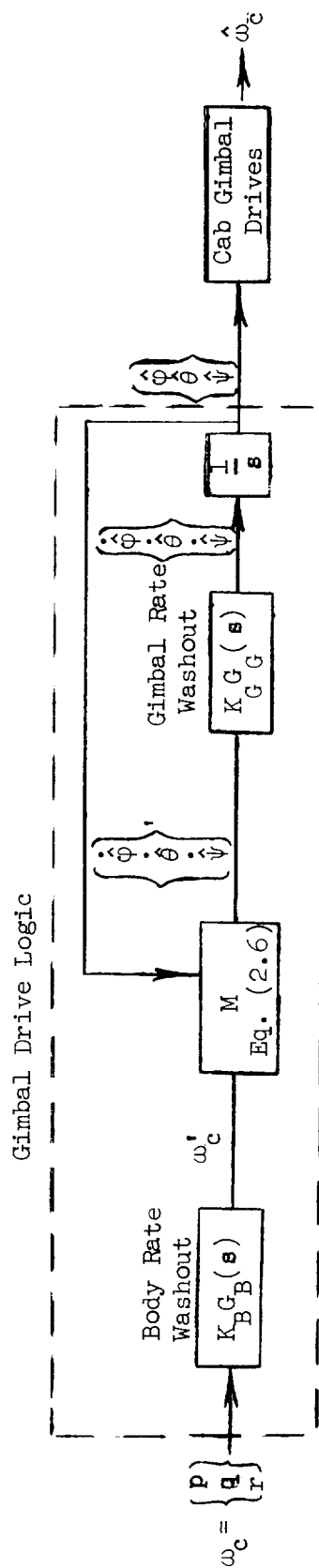
The first term in Equation (4.13) can be kept arbitrarily small so its integrals can be kept arbitrarily small. The second term, however, is uncontrolled, so the attitude history must be appropriate to keep its integrals small.

4.2 Washout Circuits for Rotational Channels. — Much of the discussion relating to generating translational drive signals is applicable to rotation channels. Figure 4.3 presents a candidate set of logic. In the sequel we assume $K_G = 1.0$. We immediately note that washout in the body frame eliminates coupling but only indirectly limits the gimbal angle quantities, while gimbal washout is very good at limiting but introduces coupling. Furthermore, it is in general desirable to keep rotation angles small to avoid anomalous specific force cues due to coupling in the translation channels.

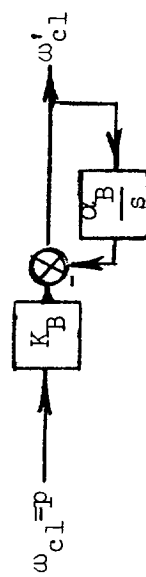
A procedure which appears feasible for choosing the parameters in Figure 4.3 is to start with $K_B = 1.0$, and $\alpha_B = \alpha_G = 0$. Next the following three steps are taken:

- 1) Set K_B as small as tolerable for the task and pilot involved.
- 2) If K_B is non-zero, then set α_B at a level suitable for removing unwanted specific forces created by tilts.
- 3) If α_B is non-zero and undesirable residual tilts accrue during simulation experiments, adjust α_G to the smallest permissible value for compensating this offset.

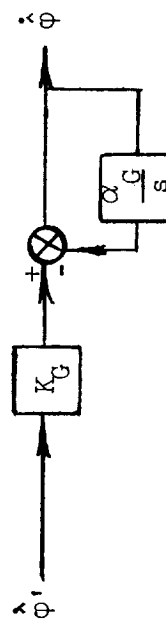
Typical values of $K_B = 0.5$ and $\alpha_B = 0.5$ have been used successfully.



(a) Gimbal drive logic with two washout circuits



(b) First channel of body rate washout. Other channels assumed to have this form also.



(c) First channel of gimbal rate washout. Other channels assumed to have this form also.

Figure 4.3. Gimbal Drive System with Body and Gimbal Washout Logic.

4.3 Multi-channel Residual Tilt. - Just as with the single channel case small offset tilts can be used to generate small, low frequency specific force cues in the lateral and longitudinal directions relative to a cab fixed frame. Logic to use this effect must avoid introducing significant rotations or rotation rates. A small rotation signal which can be added to the one generated in the logic of Figure 4.3 will be defined.

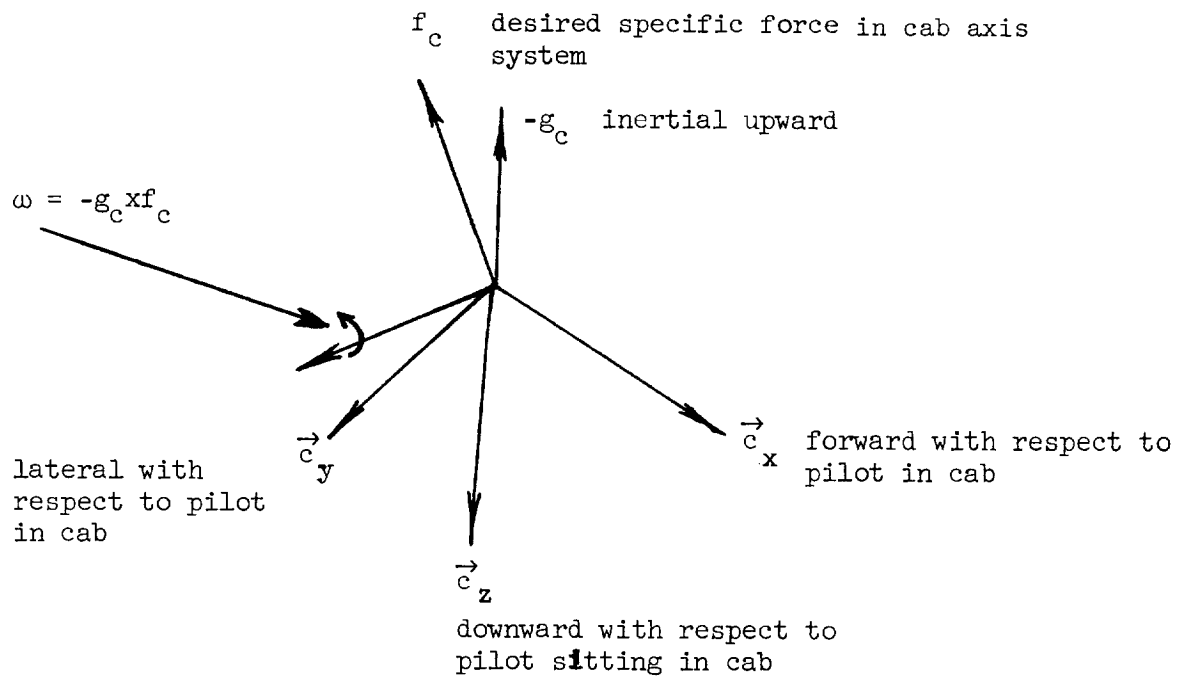
In the multichannel case the tilt angles necessary to obtain a certain specific force sensation in lateral and longitudinal directions could be computed directly. However, an alternate feedback scheme which obtains these angles has been implemented in the Ames All-Axis Simulator. In this scheme small rotation rate signals are generated that drive the cab towards an attitude which gives appropriate force cues. Figure 4.4 gives a detailed picture of the geometry involved. It is desired to achieve a specific force sensation by placing g in a direction along f_c , although magnitude cannot be controlled. Since we can only handle small lateral and longitudinal forces we assume

$$f_c \approx f_c'' = \begin{pmatrix} \text{small } f_{c1} \\ \text{small } f_{c2} \\ -32.2 \end{pmatrix} \quad (4.14)$$

and rotate the cab about $-g_c \times f_c$ until this term is zero since both are parallel. Notice both terms are coordinatized in the cab frame so the rotation vector ω is also in a cab (body) frame.

Hence, for a desired specific force from residual tilt of the form of Equation (4.13) the circuit given in Figure 4.5 gives the right forces when the proper attitude is achieved. Note the provision for washout in the form of a low-pass filter, so that only the slowly varying force terms which will not yield large anomalous rotation cues are achieved through tilting.

It should be noted that the feedback nature of residual tilt generation contains some useful washout properties desirable in the rotation channels. This circuit, for the small longitudinal and lateral



Note that f_c is fixed in the cab frame. Rotating this frame along the ω axis, perpendicular to f_c and g , brings the two into alignment.

Figure 4.4. Residual Tilt Geometry.

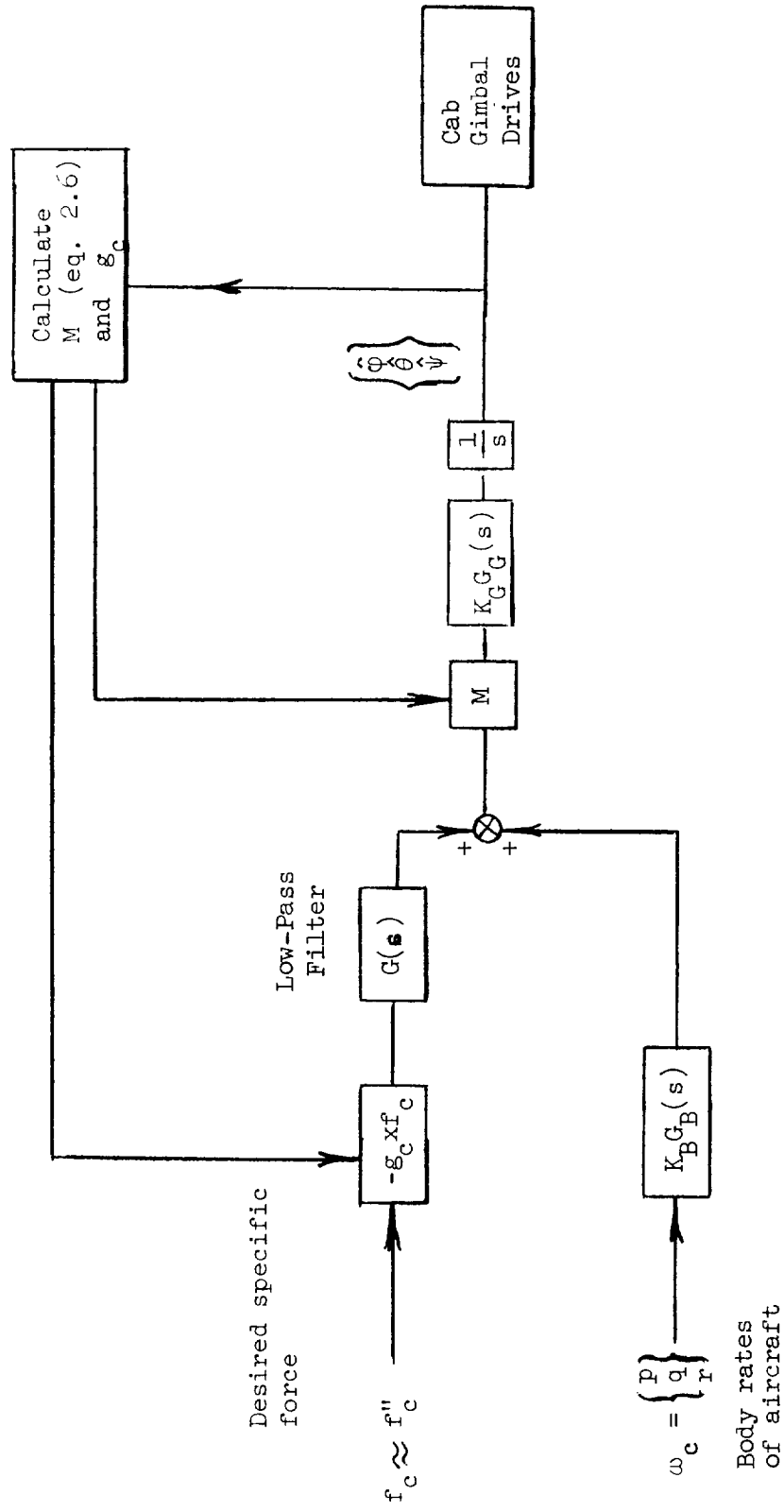


Figure 4.5. Gimbal Drive System Logic Including Residual Tilts.

forces permitted, will restore the cab to a near-upright position when the aircraft rotation rates ω_c have become negligible. The upright cab position only assures restoration to small roll and pitch angles. If it is desired that the feedback principle restore the yaw angle to a small value, an appropriate artificial signal proportional to yaw angle can be added to the residual tilt channel.

4.4 Traditional Techniques as Extended for the All Axis Motion Generator. -

For completeness this section combines the circuits of sections 4.1, 4.2, and 4.3 in one picture. In fact, any mechanization of such circuits is very much simulator and task dependent. In Appendix B the details of a particular circuit which is being used for certain tasks is presented.

Figure 4.6 presents the general extension of classical principles to a 6-degree of freedom simulator. It should be noted that the final integrations to obtain position drive signals and the last filter have been combined since they are simply cascaded linear elements. Also note that if cab reference washout is included, a signal corresponding to specific force due to gravity must be excluded as before.

4.5 Washout Circuit with Coordinated Translational and Rotational Drives. -

In the previous section no particular emphasis was placed on coordinating forces obtained from residual tilts with forces obtained from the translational drives. In this section we synthesize logic utilizing feedback principles to coordinate these effects.

Section 3.4 illustrated the concept by which translational and rotational drive channels can be coupled to improve the specific force sensations. The translational drive provides the high frequency force variations and residual tilts provide the low frequency force variations. As was mentioned this concept is applicable for providing lateral and longitudinal force variations felt by a pilot. The magnitude of these variations must be some small fraction of $1g$ or the rotation angles (residual tilts) become large. The technique cannot be applied to improve normal force cues. Hence, for the normal force channel we are restricted to the capabilities of the vertical drive channel which can

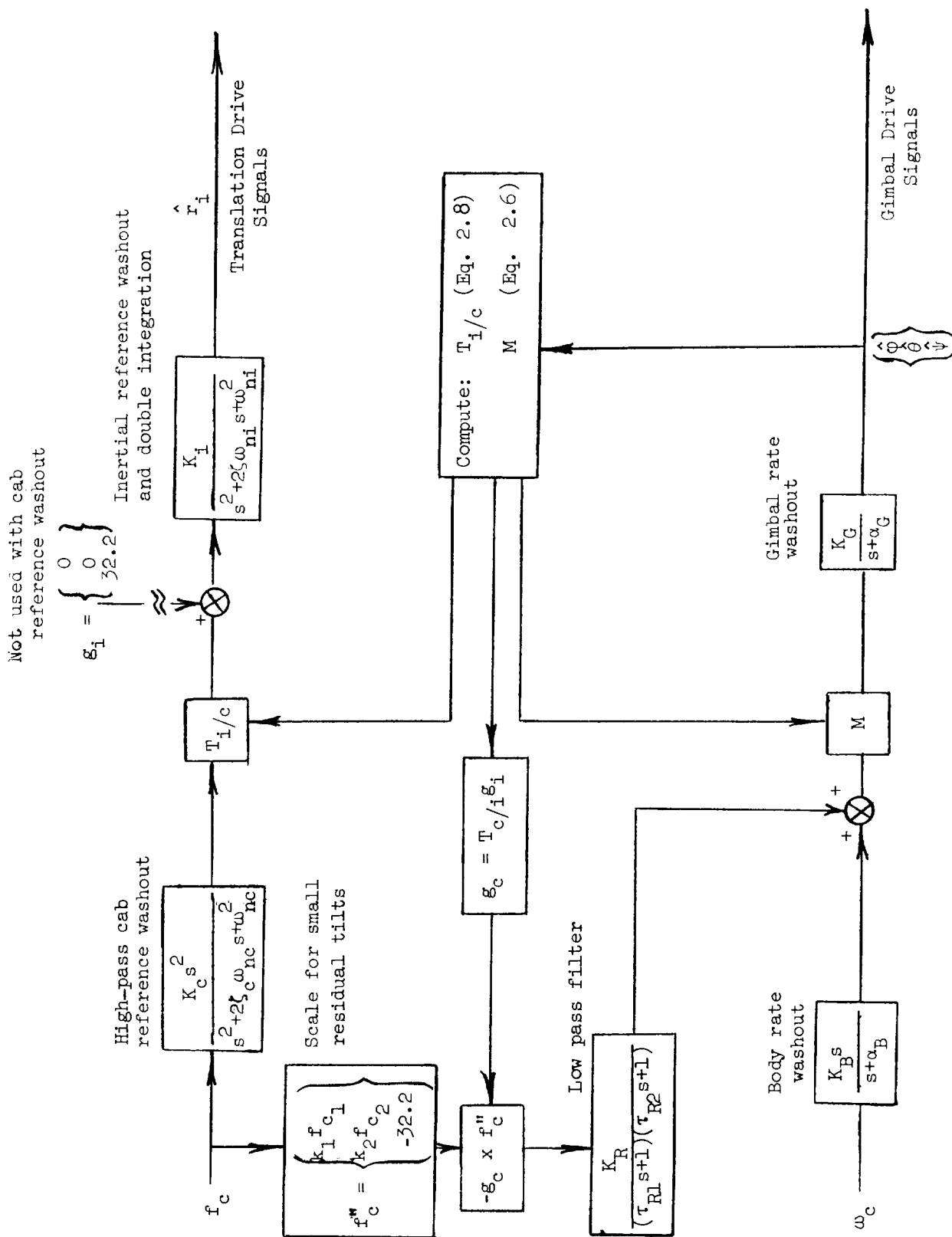


Figure 4.6. Logic for Drive Signal Generation with Washout for Full Six Degrees of Freedom.

only provide high-frequency components of the normal force variations. This section will develop a six-degree-of-freedom washout circuit based on this coordinated philosophy. To start, we split the desired specific force in cab reference into two parts as follows:

- 1) The normal force variations from lg (a scalar)
- 2) A 3 vector comprised of the lateral and longitudinal forces plus a constant lg normal force.

The normal force variations (Part No. 1) are then scaled and sent through a high-pass filter and transformed to inertial coordinates to provide part of the translational drive command acceleration. This portion uses the washout techniques described in Section 3.

The lateral and longitudinal forces are scaled such that the magnitude of their excursions is less than about $.2g$. This value is selected so that residual tilts will be very modest when they occur in providing low frequency force sensation.

Next we consider a technique whereby the two horizontal drive commands of the All-Axis Motion Generator are coordinated with the rotational drives.

We shall, using feedback principles, find washout logic which provides both washout for the tilt angles as well as acceleration commands for the horizontal drives.

Let

$$f_c^* = \begin{pmatrix} k_1 f_{c1} \\ k_2 f_{c2} \\ -32.2 \end{pmatrix} \quad (4.15)$$

= scaled force for part No. 2 in cab coordinates.

Then the drive acceleration in inertial coordinates for providing this force is

$$\ddot{\hat{r}}_i = T_{i/c}(\hat{\phi}, \hat{\theta}, \hat{\psi}) f_c^* + \hat{g}_i \quad (4.16)$$

If we examine the components of (4.16) we find that the 3rd component

$$\ddot{\hat{r}}_{i3} \approx 0 \quad (4.17)$$

when the angles $\hat{\theta}$ and $\hat{\phi}$ are small. This acceleration component will be forced to be zero for subsequent operations.

Define

$$f_i^* = T_{i/c}(\hat{\phi}, \hat{\theta}, \hat{\psi}) f_c^* \quad (4.18)$$

Now the cross product operation discussed in the previous section can be used to provide a rotation vector direction in the inertial frame. Recall that this rotation drives the transformation to null the cross product. Expanding this cross product we find

$$\frac{-\hat{g}_i}{|\hat{g}_i|} \times f_i^* = \begin{pmatrix} -f_{i2}^* \\ f_{i1}^* \\ 0 \end{pmatrix} \quad (4.19)$$

If we examine (4.16) we find that

$$\begin{aligned} \ddot{r}_{i1} &= f_{i1}^* \\ \ddot{r}_{i2} &= f_{i2}^* \end{aligned} \quad (4.20)$$

Hence, a drive which nulls the cross product also nulls the translational acceleration since the same quantities are involved. The quantities of 4.20 need not only be nulled but their double integrals (i.e., positions) must be constrained. This constraint is accomplished by enclosing a shaping network with an s^2 in the denominator in a feedback loop as shown in Figure 4.7. The heavy line of the figure shows the feedback closure. It can be shown that if the inputs, f_c^* , are constrained then the position drives, \hat{x}, \hat{y} , will be constrained provided the feedback loop is stable. Stability is achieved by the particular form of the numerator of the shaping network and the selection of appropriate gains. The closed loop character of this circuit will be discussed in more detail subsequently.

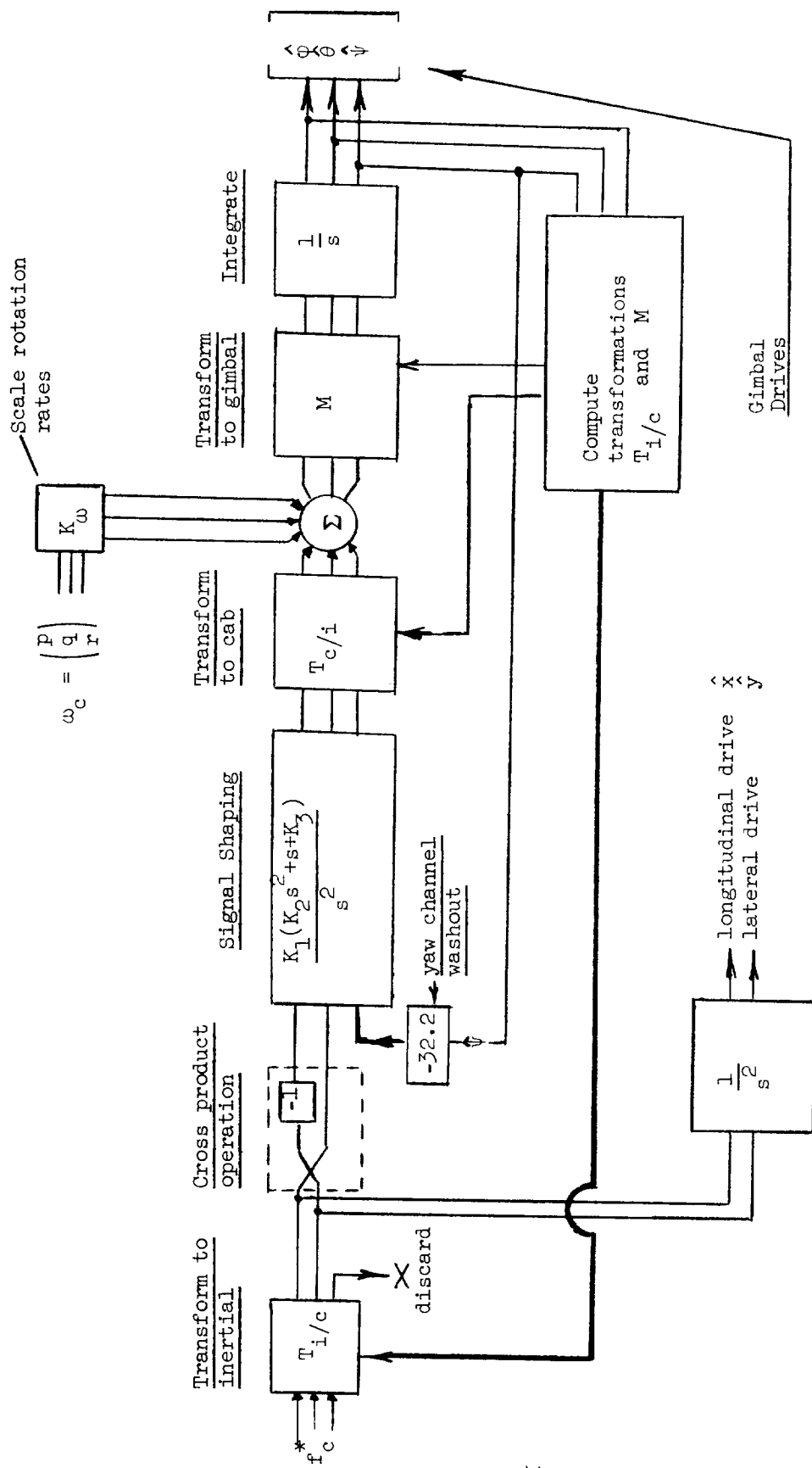


Figure 4.7. Circuit Coordinating Gimbal and Translational Drives.

As was the case for the washout circuit of the previous section, there is no command from the cross product to drive the yaw gimbal to zero (washout about the g vector). This is quite obvious from Equation (4.19) where the third component is identically zero. In Figure 4.7, the quantity $\hat{\psi}$ is fed into the third channel of the shaping network to provide the required washout for rotations about the g vector (local vertical).

The output of the signal shaping network can be interpreted as washout rates in inertial axes. These rates are transformed to cab axes and summed with the desired body rates. In this washout circuit the desired body rates are defined as the product of the scale factor, K_ω , and the body rates, ω_c , which come from the computer simulation of the aircraft.

The closed loop character of the washout circuit can be seen by assuming the small angle approximation for the $T_{i/c}$ transformation and examining components of the vector f_i^* .

$$f_i^* \approx [I + \rho x] f_c^* = \begin{bmatrix} f_{c1}^* - \psi f_{c2}^* + \theta f_{c3}^* \\ \psi f_{c1}^* + f_{c2}^* - \phi f_{c3}^* \\ -\theta f_{c1}^* + \phi f_{c2}^* + f_{c3}^* \end{bmatrix} \quad (4.21)$$

The first component of f_i^* is

$$f_{i1}^* = (f_{c1}^* - \psi f_{c2}^*) - 32.2\theta \quad (4.22)$$

Now if we interpret the bracketed term in (4.22) as the input and the θ term as the feedback we see part of the loop closure. By assuming the product transformation

$$T_{c/i} \cdot M = I \quad (4.23)$$

and referring to Figure 4.7, the linear feedback circuit shown in Figure 4.8 can be obtained for the pitch channel.

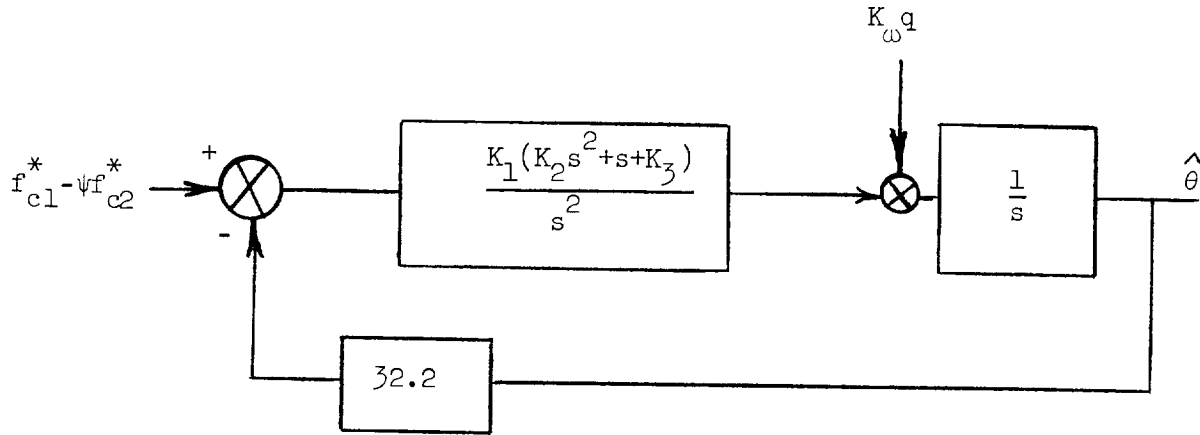


Figure 4.8. Linearized Equivalent Circuit of Pitch Channel of Coordinated Washout.

The other two channels can be shown to be equivalent to Figure 4.8. For those familiar with stability analysis it should be obvious that the gains K_1 , K_2 , and K_3 can be selected to give a stable system. For the washout circuits like the above which were used in the study, the gains were set to obtain an appropriate transient response.

By examining Figures 4.7 and 4.8 the following properties of this feedback circuit can be summarized:

- a. For small amplitude disturbances the translational forces are properly presented for all frequencies.
- b. Anomalous rotational rates would require adjustment depending on the available linear travel and the rapidity of the force variations.
- c. For a constant force the dynamic characteristics are such that the cab will arrive at the null linear position in the steady state. This occurs as a result of $K_3 > 0$. The cab will be tilted to provide the force in the steady state solution.
- d. Rotational rate commands are washed out at a speed dependent on gain settings. Undesired specific forces are eliminated at the expense of anomalous rotations.

e. The third channel of the circuit is used for washout of the yaw gimbal angle $\hat{\psi}$.

Hence, this circuit has many of the characteristics desired of motion command logic. To obtain the complete six degree of freedom circuit we need add the accelerations for giving the high frequency components of normal force variations. This added logic is shown in Figure 4.9. As noted from the figure the high pass filter in cab reference is used to remove low frequency components of normal force variations. The output of this filter (a scalar) is multiplied by the third column of the transformation, $T_{i/c}$. This provides a 3 component acceleration in the inertial reference for giving normal force sensations. The two accelerations from Figure 4.7 are appropriately added to this 3 component vector and then doubly integrated to give the translational drives.

Some inertial washout given by the gains $K_{\hat{r}}$ and $K_{\hat{f}}$ is shown in Figure 4.9. It should be recalled from previous discussion that cab reference washout does not totally constrain the translational drive components. Experience has shown, however, that the drifts of the two integrators when $K_{\hat{r}}$ and $K_{\hat{f}} = 0$ are small. Hence it is intended that the gains $K_{\hat{r}}$ and $K_{\hat{f}}$ be set experimentally at their lowest permissible values.

Although this circuit appears to have many desirable properties, it still must be tested and possibly modified based on the results of such tests.

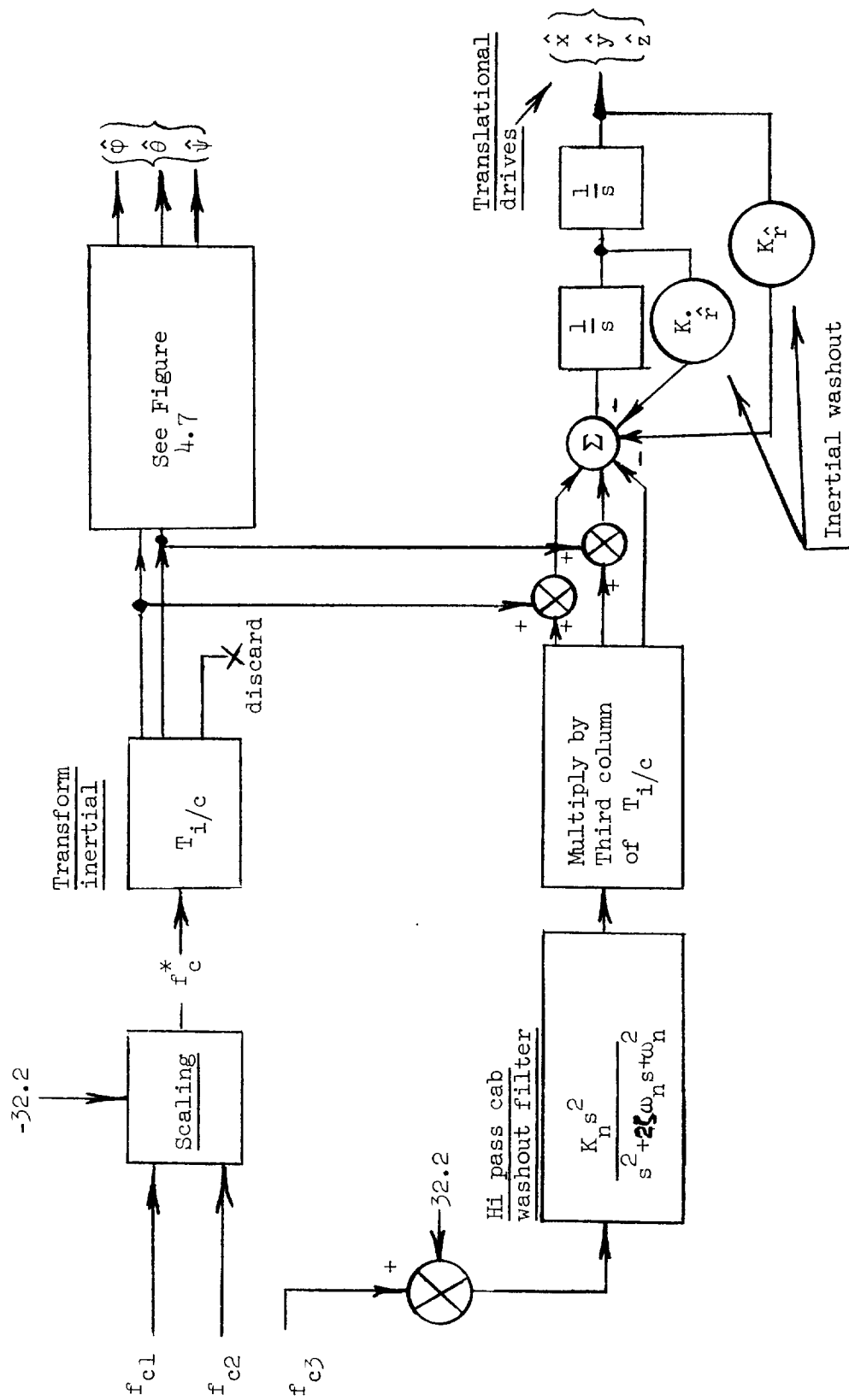


Figure 4.9. Six Degree of Freedom Washout Circuit Coordinating Translational and Rotational Motion.

SECTION 5

EVALUATION OF WASHOUT CIRCUITS

Previous sections illustrated several promising techniques for washout circuitry for multi-degree of freedom motion simulators. Each technique requires the determination of various parameters (scaling of inputs, network time constants, etc.) The choice of a particular technique and these parameters represents a particular compromise between the true motion that the pilot should sense and the motion cues that actually can be realized with the motion generator. At this point, a difficult problem is encountered. We must find some testing and evaluation procedure which (a) determines the "best" set of parameters to use in a given configuration and (b) measures the effectiveness of a given configuration. This section discusses the results of research on testing and evaluation procedures.

5.1 Requirements for an Evaluation Procedure. - If only one washout configuration were to be tested, and 'reasonable' parameters for it were known from prior experiments, an efficient search technique for improvement might be implemented by using a particular task and trying different values of parameters. However, the more general problem involves the following considerations.

- 1) The procedures should always give comparisons of particular washout configurations with the two absolute extremes of real flight and fixed base simulation. The first extreme implies that a combination of real flight tests and simulations would be necessary for evaluation unless a flight task with only limited motion (i.e., motion which the simulator can carry out completely) is used.
- 2) Good performance indexes to measure how well a pilot performs a given task in the simulator must be defined. This would permit analysis of the sensitivity of a pilot to motion cues and hence indicate their relative importance. Pilot opinion provides one such index but quantitative, less subjective measures such

as mean-square average errors between actual and desired pilot response are also desirable.

- 3) Although a particular task and performance index might be found so that 1) and 2) above are satisfied, there remains the problem that the effectiveness of a washout circuit for one task may not prove its suitability for another task since the relative importance of motion cues can be task and aircraft dependent.

These considerations make the design of testing and evaluation procedures difficult. In this investigation, for example, a first attempt at defining a test and evaluation procedure employed the simulated task of performing a landing approach with a jet transport. Using pilot comments as an evaluation index, it was determined that the motion provided with a particular washout circuit improved the overall simulator characteristics. However, moderate changes in the washout configuration did not seem to alter their opinions. It appears that this particular task (and airplane) does not require hi-fidelity motion and hence is not a good test for washout circuits.

Discussions with Ames scientists and test pilots indicated that the importance of motion cues is amplified in aircraft with degraded handling characteristics. If the landing task had been redefined with a poor aircraft, however, no comparison of simulation with realistic feel could be accomplished without actually performing the test with an airplane.

5.2 Definition of a Promising Evaluation Procedure. - In contrast with the landing task, simulation of a relative position task, such as would occur in formation flying or refueling missions, appeared to offer better prospects. If a lead aircraft (formation flying) or a tanker (refueling) flies at a constant altitude and velocity, then the All-Axis Motion Generator can theoretically provide proper motion cues if the pilot is adept enough to stay within the 18 foot cube position limits of the generator. The word theoretical is used since spurious (anomalous) motions will always exist due to imperfections in the mechanical systems associated with the cab drives (see Appendix A).

Experiments were conducted to see if the formation flying task could be used in testing washout circuit configurations. The primary object of these experiments was to determine if this task could give comparisons between completely realistic motion and fixed base (no motion). Washout circuits, of course, would give intermediate motions.

Tests were conducted utilizing a variety of simulated aircraft and lead airplane motions. Several pilots took part in the tests, and, as will be seen in the subsequent descriptions, all indications are that significant differences exist between real and fixed base motion for this task. Hence, it appears quite appropriate for evaluation of washout circuits. Subsequent paragraphs describe the formation flying task and the experiments which have been conducted.

5.3 Description of the Formation Flying Task. - Elements of the formation flying task simulation are illustrated in Figure 5.1. The pilot in the cab is given a visual display generated by the REDIFON. The display consists of a model of the Convair 990 where the REDIFON camera is initially positioned directly behind the 990. A sketch of the TV display for initial conditions is illustrated in Figure 5.2. Shown also in Figure 5.2 are the approximate boundaries for the lateral and vertical drives of the All-Axis Motion Generator. When motion is used the pilot must control the simulator to remain within these boundaries or soft limits are reached which cause erroneous motion cues.

With reference to Figure 5.1, the pilot controls are stick, rudder, and throttle. These quantities plus initial conditions are the inputs to the aerodynamic simulation. A constant head wind (approximately 140 knots) is used in the problem and the aircraft is initially trimmed so that initial transients of the problem are very small. The aerodynamics used are representative of a small twin jet transport. Table 5.1 gives the characteristics of the aircraft which were simulated. The roll damping and roll coupling terms are varied to give the values of lateral handling characteristics which are referred to herein as GOOD, FAIR, and POOR. Six degrees of freedom are simulated for the aircraft and visual display. Longitudinal motion is the only motion cue not provided to the pilot. This cue was eliminated since the pilots had trouble with

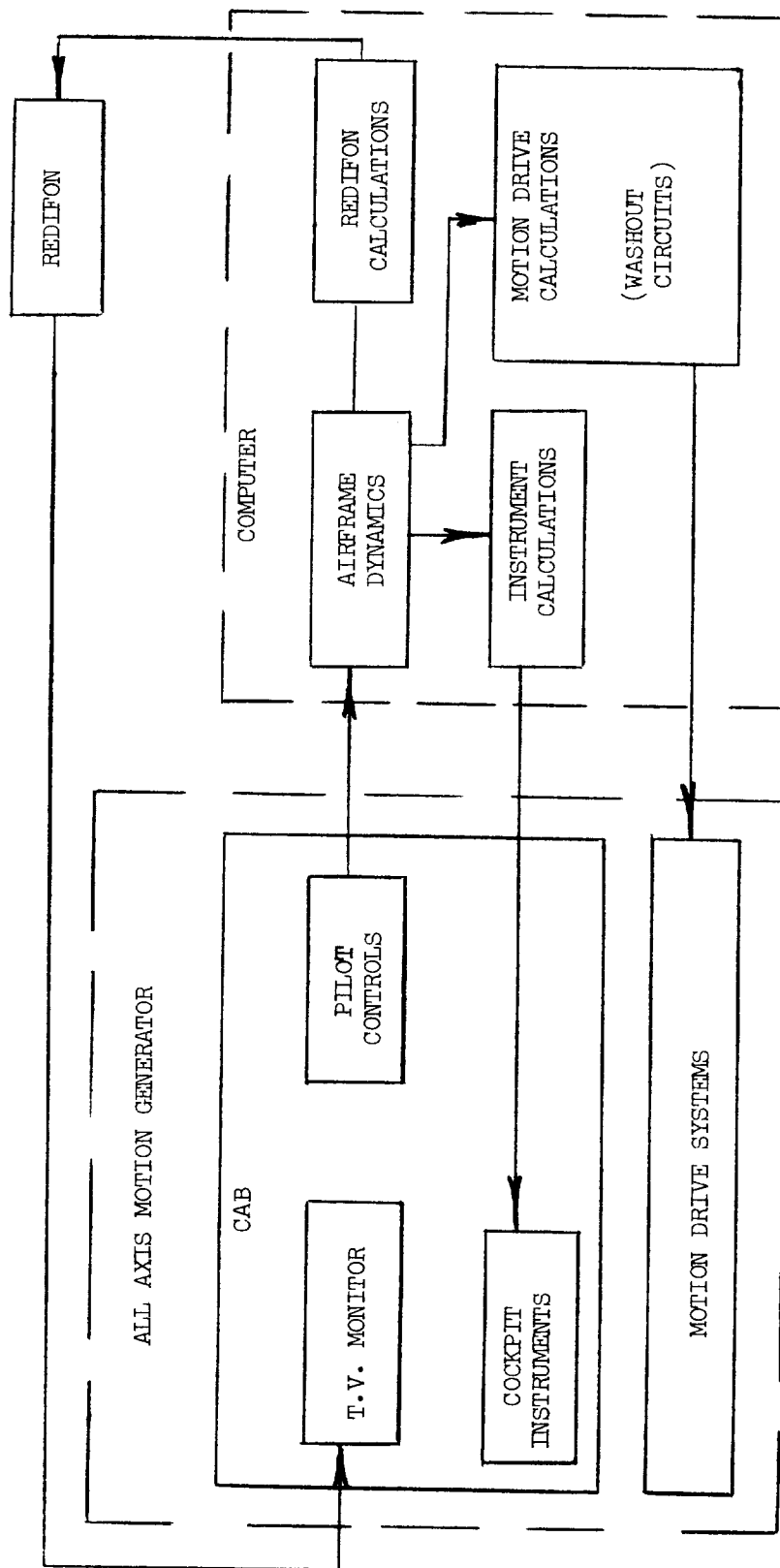


Figure 5.1. Block Diagram of a Pilot Control Simulation Using the All-Axis Motion Generator.

limits in the longitudinal channel of the motion simulator. Visual cues (depth perception) are not sufficient in the two-dimensional TV display to permit the pilot to tightly control the longitudinal separation.

The motion drive calculations shown in Figure 5.1 are effectively one to one relative motion. That is, no washout is used when motion is given to the subject. The motion drive systems are disengaged for the fixed base data.

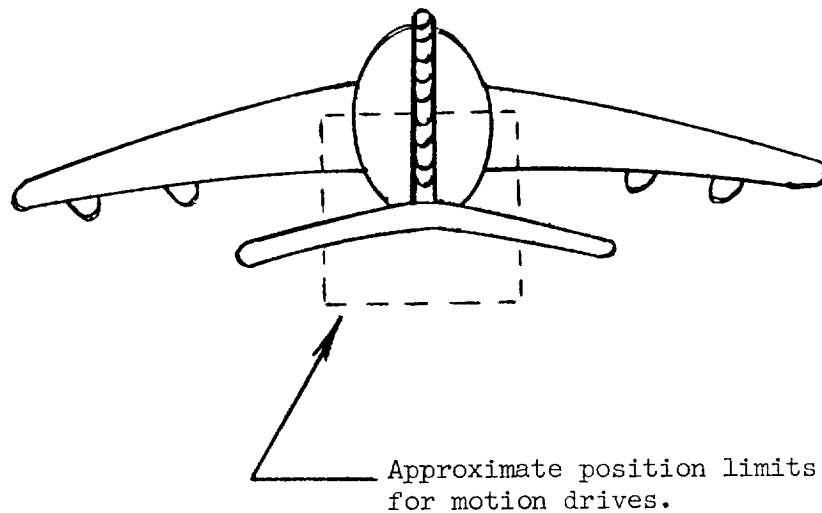


Figure 5.2. Sketch of Visual Display for Formation Flying Task.

The REDIFON calculations shown in Figure 5.1 include a random forcing function for the REDIFON vertical and lateral drive. This signal has peak amplitudes of about 3 feet and could be reasonably well approximated by zero mean white noise through a 100 second time constant first order filter.

The subject's task is to hold the Convair 990 in the middle of the TV display; that is, in the initial condition position sketched in Figure 5.2. For each condition of the airframe and motion type the subject is requested to perform this task for about two to three minutes. On line calculations of the performance are made of mean and variance of the three position errors where

TABLE 5.1
CHARACTERISTICS OF SIMULATED AIRCRAFT
Physical Properties

\bar{c}	11.08	I_X	125000.	I_{XZ}	8.25
b	71.2	I_Y	120312.	m	777.5
s	690.	I_Z	234375.	X_p^*	30.

Derivatives** (Stability Axis)

C_{D_0}	.098			$C_{\ell_r}(\alpha = 0)$.2
C_{D_α}	.377			$\partial C_{\ell_r} / \partial \alpha$.76
$\partial C_{D_\alpha} / \partial \alpha$	1.82			$C_{n_p}(\alpha = 0)$	-.025
$C_{\ell_\beta}(\alpha = 0)$	-.0653	-.1722	-.1722	$\partial C_{n_p} / \partial \alpha$	-.93
$\partial C_{\ell_\beta} / \partial \alpha$	-.253	-.506	-.506	$C_{L_0}(\alpha = 0)$.375
C_{ℓ_p}	-.44	-.22	-.11	C_{L_α}	5.35
$C_{\ell_{\delta_a}}$	-.1722			$C_{L_{\delta_e}}$.302
$C_{\ell_{\delta_r}}$.021			C_{m_q}	-12.3
C_{m_α}	-1.022			$C_{m_{\dot{\alpha}}}$	- 4.01
$C_{m_{\delta_e}}$	- .923			C_{n_β}	.1
$C_{n_{\delta_r}}$	- .1			C_{n_r}	- .32
C_{Y_β}	- .8				

* Pilot position ahead of cg (ft).

** Where three values are given they are for the aircraft in the order GOOD, FAIR, POOR from left to right in the table.

$$\text{Mean of error} = \frac{1}{T} \int_0^T \text{error}(t) dt$$

$$\text{Variance of error} = \frac{1}{T} \int_0^T (\text{error}(t))^2 dt - (\text{Mean})^2$$

Since the random forcing function comes from a magnetic tape, the problem disturbances are nearly identical for all cases and all subjects. The standard deviation is the square root of the variance. One should not attempt to deduce that the above quantities are statistical. They are simply a readily calculated performance measure for the experiment.

The order of airframes in carrying out the test was GOOD, FAIR, POOR. The subject was given the fixed base mode for familiarization for each airframe. In some cases the subjects requested motion for this same purpose. Following familiarization the data run with motion was attempted. If the subject could control the problem for the desired time, the next problem was begun. Otherwise, the subject was allowed additional trials with the same motion. The fixed base data were taken following the motion run for each case. Some subjects also requested more than one trial for the fixed base data run.

In addition to the performance calculations, and questionnaire data, other quantities were also noted. In particular, strip chart recordings were made of about 24 quantities and FM tape records were made of 13 relevant quantities which give time histories of pilots visual and motion cues and his control output for each case. Following the completion of the tests the subjects were interviewed for comments and were asked to fill out a questionnaire.

5.4 Discussion of Pilot Questionnaire Data. - The results of the pilot response to the questionnaire are shown in Table 5.2. As noted on the table, the number of pilots checking a given column is indicated. Six Ames test pilots took part in the simulation tests. Two of these six flew the simulated task for data runs on two different occasions. The questionnaire results are for the first trial only.

In reviewing the answers to questions 1, 5 and 6, one sees that overall "fair" rating for motion and unacceptable rating for fixed base

TABLE 5.2

SUMMARY OF PILOT QUESTIONNAIRE RESULTS

	EXCELLENT	GOOD	FAIR	POOR	UNACCEPTABLE
1. How well do you think you could determine the boundary between UNSATISFACTORY and UNACCEPTABLE handling qualities for a formation flying task? *					
a) Moving Base		3	1	2	
b) Fixed Base			2	1	3
2. ** How well did you perform the task?					
a) Moving Base		2	1	3	
b) Fixed Base				4	2
3. How realistic was the motion fidelity with respect to the visual display?	1	1	2	2	
4. How helpful was the motion in performing the task?	2	1	3		
5. If this task and simulation were used on an arbitrary aircraft not necessarily requiring formation flying, how well would it aid in evaluating handling qualities? Note: Formation flying could be simulated for many points in the flight envelope.					
a) Moving Base		2	1	1	1
b) Fixed Base		1		1	3
6. Rate your impression of the usefulness of this simulation as a training device for formation flying or refueling.					
a) Moving Base	1	2	2	1	
b) Fixed Base		1	1	2	2

* Note: Number in column indicates the number of pilots with indicated rating.

** Two of the pilots rated this question on the basis of the airplanes. That is, they rated their performance better (as it was) for the GOOD airplane than for the POOR. For simplicity, the average rating was used in the summary.

TABLE 5.2 (Con't)

		MORE DIFFICULT	SLIGHTLY MORE DIFF.	ABOUT SAME	LESS DIFFICULT	SUBSTANTIALLY EASIER
7. Rate difficulty of the task in relation to real formation flying.						
a) Moving Base		6				
b) Fixed Base	* 3	3				
** 8. Rate difficulty of the task in relation to a real refueling task.						
a) Moving Base		4				
b) Fixed Base	* 3	1				

	ALWAYS	OFTEN	OCCASIONALLY	RARELY	NEVER
9. Were audible simulation noises evident?					
a) Moving Base	1	4	1		6
b) Fixed Base					
If so, were they distracting?					
a) Moving Base		3	2		1
b) Fixed Base					6
10. Were drive vibrations evident?	1	3	2		
If so, were they distracting?		3	2	1	
11. Did you have any tendency toward disorientation?					
a) Moving Base			2	2	2
b) Fixed Base		1	2	1	2

* Three pilots rated questions 7b and 8b by checking outside the indicated columns. This notation meant "very" much more difficult.

** Two pilots did not answer question 8 as a result of inexperience with the real refueling task.

is indicated. Answers to questions 2a and 4 generally imply the overall impression that the motion was considered helpful. Question 2b shows that without motion there was general agreement between pilots and their performance was poor to unacceptable.

The spread in answers to question 3 is believed traceable to the simulator motion drive anomalies (See questions 9 and 10). Some pilots were more aware of these deficiencies than others.

Question 5 was introduced to see whether pilots thought a formation flying task might be useful in overall handling qualities evaluation. The reason for the question is that true relative motion (except for drive system anomalies) for such a task can be represented on the All-Axis Motion Generator. The answers indicate that without motion such an evaluation of handling qualities is not worthwhile. With motion it appears such an evaluation is promising and the question probably should be given further attention.

The answers to questions 7 and 8 indicate a strong agreement between pilots on the difficulty of the task compared to real problems. The reasons for this difficulty are believed to be as follows:

- a) The visual cues are not nearly as good as they would be in the real problem.
- b) The airplane used was somewhat sluggish for such a tight formation flying problem compared with aircraft on which the pilots had flight experience.

The pilots comments indicated that both items are true to some degree and which is worst depends on the individual pilot's experience.

The answers to question 9 indicate that with motion the audible noises are both evident and distracting to the majority of the pilots. This is with one to one motion where audible noise level is to some degree correlated with visual and motion cues. With washout circuitry it is believed that these audible noises will be more distracting since they will not necessarily be correlated with visual cues.

The answers to question 10 indicate that drive vibrations are both evident and distracting to the majority of the pilots. This vibration problem is believed to be caused primarily by the lateral drive channel (See Appendix A). It is recommended that some experiments be conducted to isolate this problem and correct it, if possible.

The answers to question 11 generally indicated little problem associated with disorientation, with or without motion. One pilot commented that in the fixed base cases he occasionally had problems of moving the ailerons in the wrong direction.

It is believed that the answers to question 11 will change when washout is introduced. That is, some other tests have indicated that anomalous motion can cause a feeling of disorientation.

5.5 Discussion of Measured Tracking Errors. - Table 5.3 contains the standard deviation of the tracking errors for each of the pilots. The data from Table 5.3 as summarized in Figures 5.3 and 5.4 indicate considerable differences between motion and fixed base. Generally speaking, with motion there was considerably less variance (scatter) in performance between the different pilots. The larger scatter with motion for the POOR aircraft is believed partially due to the soft limits. That is, two of the pilots reached the lateral or vertical limits and had problems resulting from the lack of proper linear acceleration cues. This is believed to have caused a larger transient than would have been encountered otherwise. The POOR aircraft is of course harder to control so this is a second factor contributing to the larger scatter.

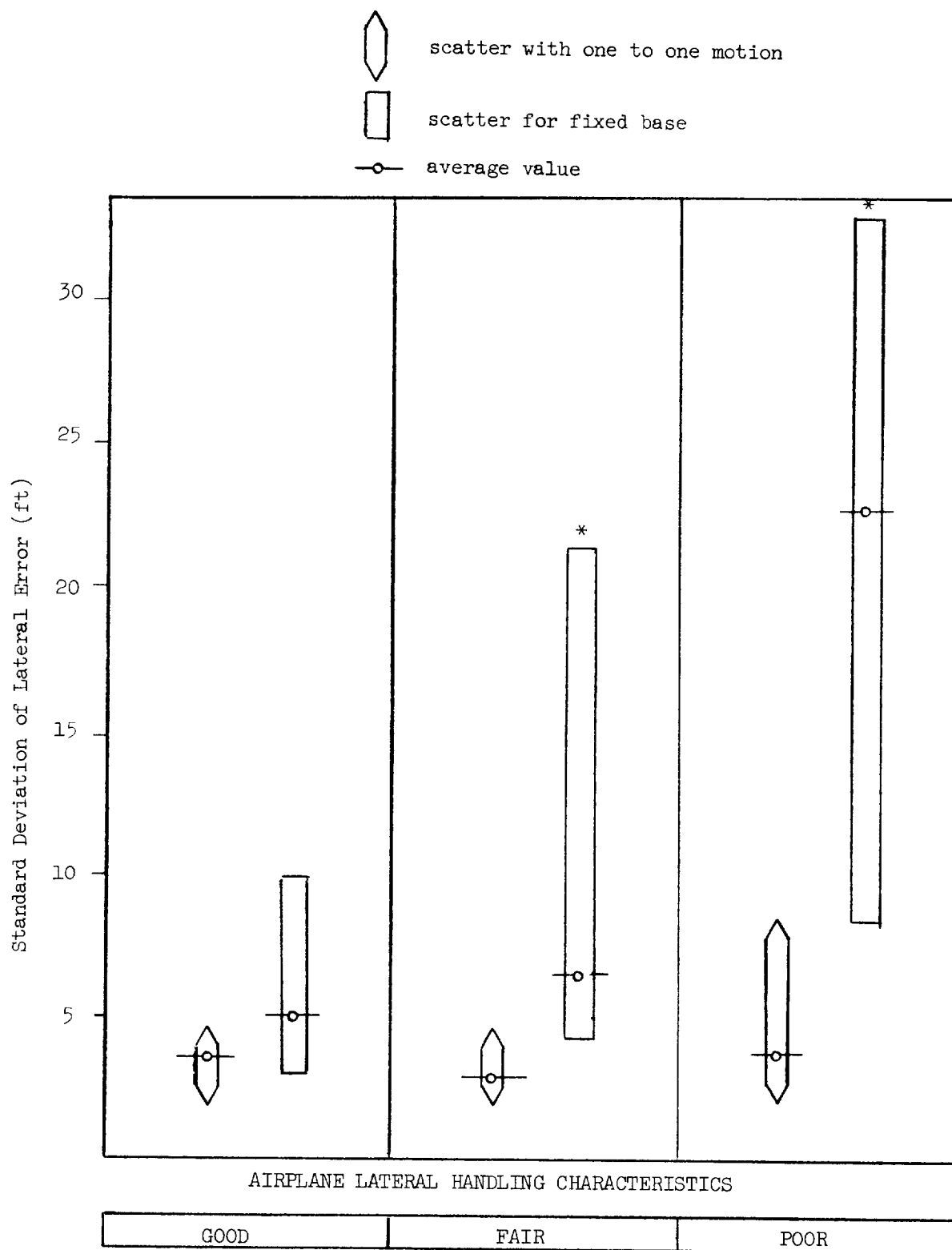
Two of the pilots (C and D) actually improved performance with motion in going through the GOOD, FAIR, POOR airplane sequence. This is undoubtedly associated with the learning process about the simulation and task. This learning process needs further investigation since it could affect results when comparisons of washout configurations are made.

Of particular note is the large scatter in the fixed base results which generally increases with the degrading of aircraft handling qualities. One of the pilots who controlled the FAIR and POOR aircrafts well with motion could not control the aircraft in fixed base.

These data emphasize the importance of motion for this type of flight task. Hence, it should provide a means of evaluating differences between various washout circuit configurations and various parameter settings.

TABLE 5.3 STANDARD DEVIATION OF TRACKING ERRORS

PILOT	AIRPLANE	MOTION	COMPONENTS			Comments
			X ft.	Y ft.	Z ft.	
A	GOOD	M	31	4.05	2.21	} changed to no rudder
		F	35.6	10	5.65	
	FAIR	M	-	2.8	1.84	
		F	-	21.6	8.85	
	POOR	M	74	7.1	4.37	Uncontrollable
		F	24.6	29.6	12	
B	GOOD	M	28	2.57	2.7	Uncontrollable
		F	37.6	4.14	12.5	
	FAIR	M	10.6	2.76	2.02	
		F	73	15	5.	
	POOR	M	70.5	3.7	2.6	
		F	99	31.8	13	
C	GOOD	M	27.8	3.44	3.14	} changed control technique (no rudder) lost at end
		F	14.9	3.56	2.14	
	FAIR	M	27.2	3.08	3.07	
		F	25.4	5.4	3.05	
	POOR	M	32	2.88	2.75	
		F	38	12.2	2.36	
D	GOOD	M	12	4.4	.94	Uncontrollable
		F	23.6	5.4	2.66	
	FAIR	M	16.3	3.34	2.78	
		F	12.4	12	3.2	
	POOR	M	19.2	2.12	2.07	
		F	-	11.7	7.5	
E	GOOD	M	-	-	-	Not available
		F	13.1	2.93	1.54	
	FAIR	M	16.2	2.4	.995	
		F	15	4	1.4	
	POOR	M	13.4	3.4	1.76	
		F	22.8	20.6	2.9	
E	GOOD	M	9.6	2.06	.945	
		F	7.65	2.61	1.01	
	FAIR	M	8.6	2.25	1.0	
		F	19.6	5.6	1.66	
	POOR	M	13.4	3	1.0	
		F	29.8	8.3	2.17	
F	GOOD	M	156.	4.0	2.22	Disturbance of target out
		F	500	4.3	1.73	
	FAIR	M	343	4.37	3.22	
		F	79	8.4	3.18	
	POOR	M	58.5	8.2	10.9	
		F	78	33	19	



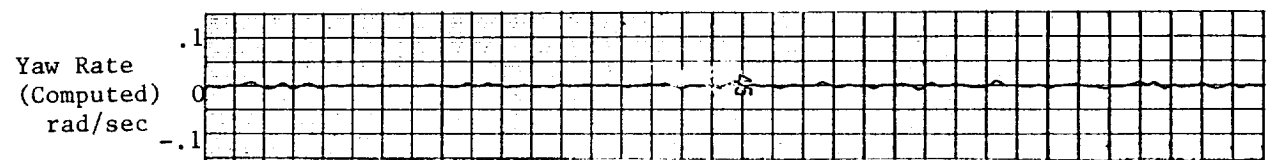
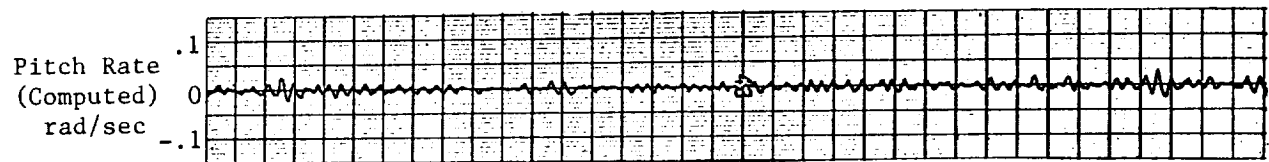
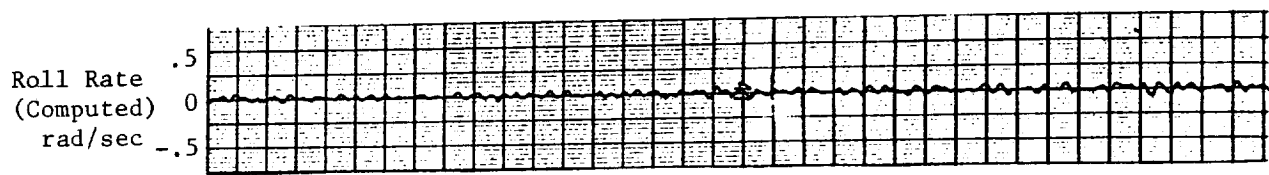
* One pilot could not control problem laterally.
 This point neglected in scatter and average.

Figure 5.4. Summary of Standard Deviation of Lateral Error.

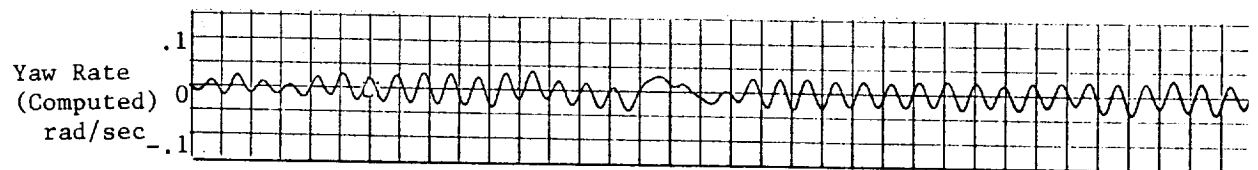
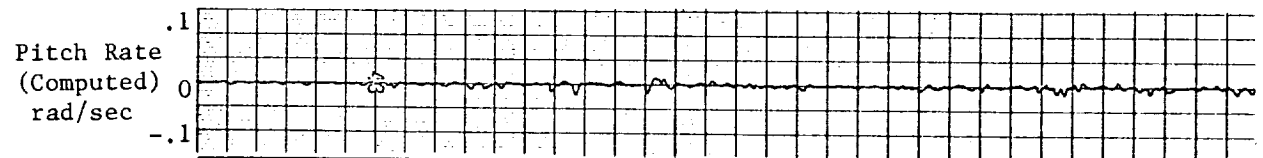
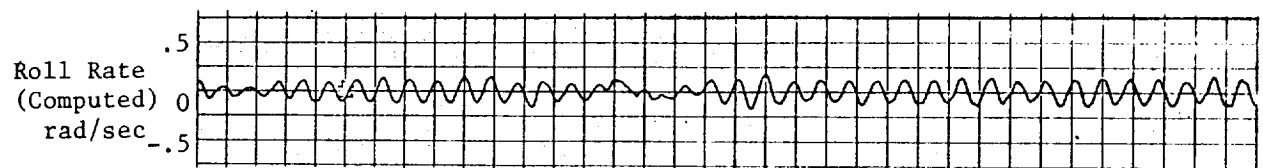
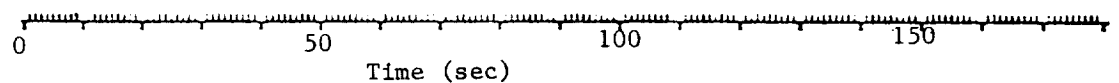
5.6 Sample Time Histories Showing Effects of Motion. - As was mentioned in Section 5.3, strip chart recordings were made of about 24 quantities. Figure 5.5 is a sample time history of some relevant quantities which are useful in understanding differences between fixed base and motion. The case shown is for the first sample for pilot E of Table 5.3 for the POOR aircraft. By comparing the time histories for motion versus fixed base one can note a significant difference. This difference is most evident in the yaw and roll rate time histories. Without motion cues the pilot is not able to damp the dutch roll mode. In the fixed base case the roll rate and yaw rate histories are somewhat similar to a limit cycle behavior in a non-linear feedback control system.

With motion the mode is either not excited or well damped. The additive damping possible from the motion cues is believed the most likely factor.

The characteristics shown here were present for all the pilots to some degree. Pilot D, who could not control the airframe fixed base, had roll and yaw rate time histories characteristic of an oscillatory unstable system.



(a) One to One Motion



(b) Fixed Base

Figure 5.5-Comparative Time Histories for POOR Airplane
Illustrating Effects of Motion Cues

SECTION 6

CONCLUDING REMARKS AND RECOMMENDATIONS

This report has dealt with and presented partial solutions to the problem of generating drive commands in simulation systems with constrained multi-degrees of freedom motion capability. Results of the work discussed herein include:

- a. A review and mathematical formulation of the basic problem of reproduction of motion cues as they would be sensed in a real aircraft.
- b. Examination of the influence of motion simulator constraints on the ability to reproduce the ideal motion cues. This examination has shown the following comments applicable for the Ames All-Axis Motion Generator.

Normal Force Cue - Cannot in general be precisely provided. Motion simulator constraints in the vertical channel force one to omit this cue entirely or to supply only scaled and/or high frequency components of the ideal motion.

Lateral and Longitudinal Force - For restricted ranges in magnitude these cues can be accurately provided. Requires use of cab tilts and the resultant anomalous rotations to do so, however. The magnitude of anomalous rotations in providing accurate force cues is dependent on the maximum allowed cab travel in lateral and longitudinal directions.

Rotational Cues - Can be precisely provided for many flying tasks. Problem arises since cab tilts can cause anomalous forces. This problem generally requires the use of anomalous rotation cues to reduce unwanted forces.

- c. Traditional single axis concepts have been extended to multi-degree of freedom cases and new washout circuits have been described and developed. Both the extended traditional approach and the new approach compromise the ideal motion in satisfying motion simulator constraints. The new configurations developed appear to offer a potentially better compromise from the following considerations.

1) The translational drives are coordinated with rotational drives by means of a feedback type washout network. This allows lateral and longitudinal force cues to be accurately provided or modified in some arbitrary fashion such as scaling.

2) Anomalous rotational cues result. However, we believe their magnitude would be smaller than that given by the traditional washout circuit design approach.

3) The parameters one selects are related to available travel, input ranges and anomalous rotational cues. As a result, evaluation of appropriate settings for a given simulation may require less experimentation than the traditional washout circuit.

The validation and improvement of washout circuits was shown to be a difficult task in itself since, in general, so much is unknown about the "best" compromise motion to give a pilot. Investigation of this aspect of the problem has yielded the following partial results.

1) Some experiments with a landing approach task of a jet transport were completed as discussed briefly in Section 5.

2) A six degree of freedom circuit employing traditional washout techniques was developed for a landing approach study of a VTOL aircraft. The washout configuration and preliminary results is discussed in Appendix B.

It would be highly desirable to define and conduct experiments to obtain better quantitative information on how important motion cues are, whether or not external variables such as drive system noise are important, etc. A start on this area involved the following:

- a. A task and simulation has been defined and tested wherein motion cues have a very measurable influence.
- b. Washout drive circuitry has been developed wherein a nearly independent control of motion cues is possible.
- c. Applicable analysis procedures have been investigated to the extent that there appears promise in gaining information to relate:
 1. Pilot subjective opinion
 2. Measured pilot performance
 3. Measured pilot response to real and anomalous cues.

These factors have laid the ground-work for conducting experiments and analyzing the results in order to obtain information on the performance indices for washout circuits.

Recommendations. - Recommendations for continued effort include

1. Completing the evaluation of the washout circuits developed for the Ames All-Axis Motion Generator. Document the results of these tests and describe the subroutines involved.
2. Experimenting with the circuits described herein to find simple methods for choosing the constants involved as a function of the type of simulation task involved.
3. Test the validity of evaluation procedures developed in Section 5.

APPENDIX A

The All-Axis Motion Generator

Table A.1 gives a NASA summary of the All-Axis Motion Generator characteristics. Some additional information about the motion generator is presented here.

Limits

The limits indicated in Table A.1 are determined by protective relays in the drive system. The quantities sensed by the relays are not accelerations or velocities at the pilot's location in the cab. Rather, they are quantities such as drive motor current which is proportional to drive torque. The drive load is not a pure inertia but includes such factors as cable stretch, structure bending, friction, play in support structure and so forth.

If any limit is exceeded in any of the channels, an automatic shutdown of all drive channels is made. These shutdowns produce a nuisance factor which could be removed by incorporation of soft limiting in the drive command circuitry.

Gimballing

The cab gimballing follows the order of

Pitch - Outer Gimbal

Yaw - Middle Gimbal

Roll - Inner Gimbal

Figure A.1 is an illustration of these rotations.

Translational Drive Systems

The translational drives are track-wheel-supports driven by electrical motors through cables. The mass of the load in the various axes follows the order

Vertical - Inner Drive - Lowest Mass

Longitudinal - Middle Drive - Middle Mass

Lateral - Outer Drive - Largest Mass

TABLE A.1 - CHARACTERISTICS OF AMES ALL-AXIS MOTION GENERATOR

Motion Generated:	<u>Acceleration</u>	<u>Velocity</u>	<u>Displacement</u>
Roll	> 6 Rad/Sec ²	4 Rad/Sec	+ 45°
Yaw	> 6 Rad/Sec ²	4.9 Rad/Sec	+ 45°
Pitch	> 6 Rad/Sec ²	2.8 Rad/Sec	+ 45°
Vertical	10 Ft/Sec ²	17.3 Ft/Sec	Maximums + 9 Ft
Longitudinal	7 Ft/Sec ²	14.1 Ft/Sec	+ 9 Ft
Lateral	7 Ft/Sec ²	14.1 Ft/Sec	+ 9 Ft

Drives: Ward-Leonard Electrical Servos
Torque motors drive through silent chains to rubber-faced sectors or to cable pulling drums.

Program: Closed-loop operation with analog computation.

General Comments:

Shut-down capability is provided at several stations. Electrical and electronic circuits are used to limit accelerations, velocities and displacements. Brakes are energized-to-release for fail-safe operation.

The one-man cab is fitted for vertical rising aircraft with stick, rudder, and throttle controls. Televised visual display is anticipated as an approach and landing aid. Displacement to a limit of travel programs the cab to drive to an initial condition of displacements and attitude.

The design permits installation of cabs having other configurations.

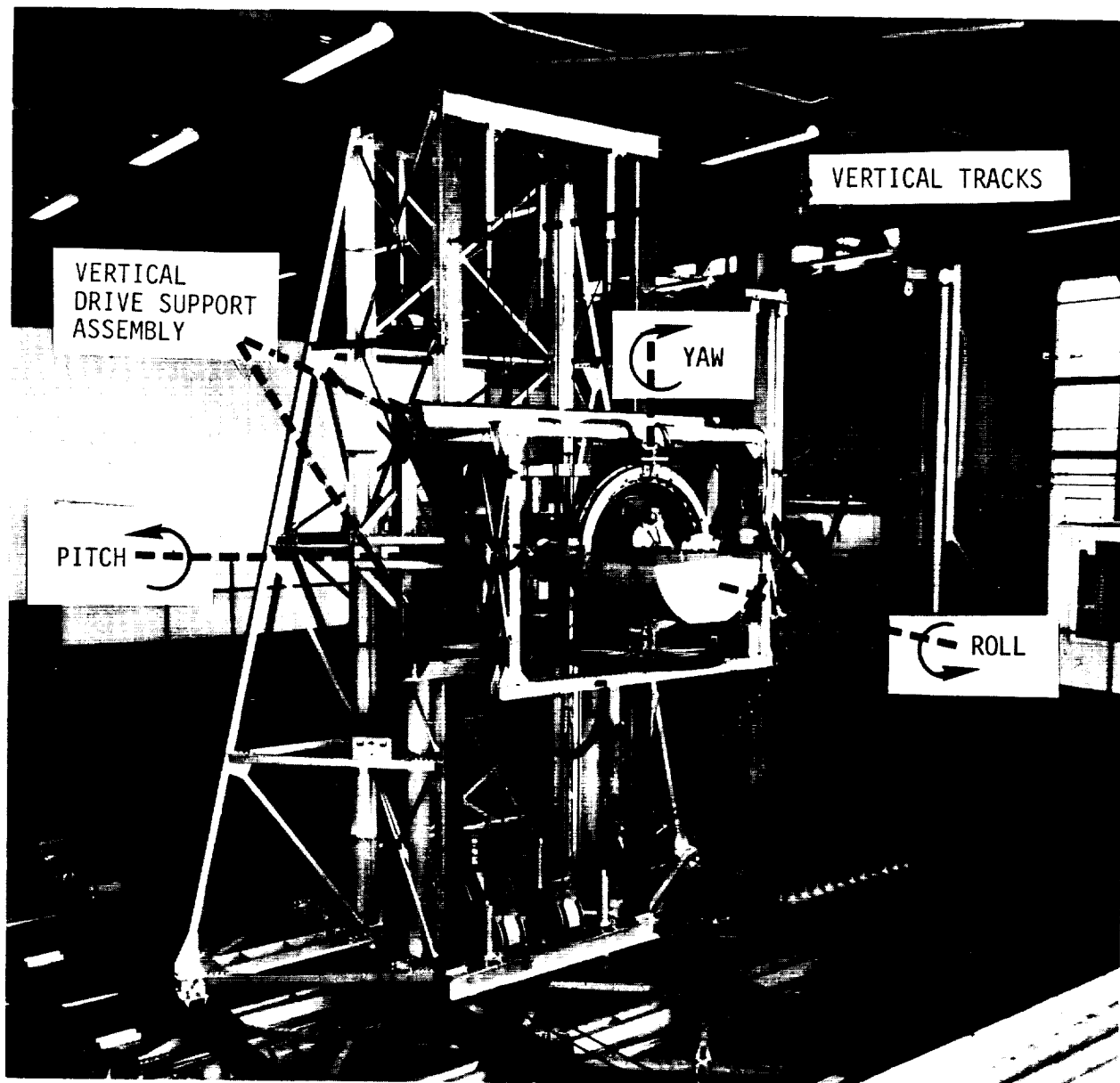


Figure A.1-The Ames All-Axis Motion Generator

The characteristics of the response of these position drive servos follows the inverse order of the mass, i.e., the lateral system is the most sluggish in response. In the longitudinal and lateral drive systems, wheels on tracks support the structure. The weight of the structure holds the wheels to the tracks.

The vertical drive has five wheels on each of two tracks to constrain the cab and gimbal structure to vertical motions. The center of gravity of the cab-gimbal structure (see Figure A.1) is considerably forward to the drive track wheel assemblies. Some evidence obtained from sinusoidal tests suggests that there is play in the drive support assembly. If the cab is driven vertically or longitudinally the weight resulting from the offset center of gravity of the cab gimbal structure would tend to hold the wheels to the vertical drive tracks. When the support structure is driven laterally, however, the offset center of gravity of the cab combined with some play in the wheels can cause anomalous side forces and yawing rates. The sinusoidal results tended to support this theory in that lateral anomalous motions are the most significant. For example, if one drives the lateral servo with about a 1 Hz signal of a very small amplitude then cab mounted lateral accelerometer output is by no means sinusoidal. Instead it appears to be dominantly damped oscillatory motion with a higher natural frequency than 1 Hz.

Such characteristics can result from the play in the actual drive assembly. Visual inspection during the 1 Hz excitation tends to support this theory. The vertical tracks appear to oscillate at 1 Hz. However, the cab lateral distance motion seen from the front of the cab has a high frequency damped oscillation excited at a 1 Hz repetition rate. Note that the visual distance measure observed includes both distance due to lateral travel of the vertical drive tracks as well as rotations about a vertical axis. Play in the wheel assembly would allow apparent lateral distance motions under the conditions tested.

Lead Compensation

The NASA tests have defined lead compensation network constants for all the drive channels. The compensation is of the form shown in equation (A.1) for the translational drives.

$$y_c = a_2 \ddot{y} + a_1 \dot{y} + y \quad (A.1)$$

y_c = a linear drive command

y = desired (calculated) linear drive position

\dot{y} = dy/dt

\ddot{y} = d^2y/dt^2

a_1 and a_2 = compensation coefficients (different numerical values for each channel). This experimentally-determined compensation causes the cab mounted accelerometer outputs to follow \ddot{y} with near zero error to modest frequencies (e.g., 1-2 Hz).

Approximate Model

Assuming lead compensation is used and anomalous motions and limits neglected then the servo response is effectively perfect for the bandwidth of interest. As a result, we can use the approximate model of a perfect servo except for the limits given in Table A.1 and the anomalous motions discussed previously.

Experimental evidence has suggested that anomalous motions are less noticeable if the simulated problem contains some rough air. In this instance the subject cannot readily distinguish the rough air from the servo anomalies. Hence, the approximate model suggested becomes more accurate for simulated pilot control problems in turbulent air.

APPENDIX B

A Six Degree of Freedom Washout Circuit for the All-Axis Motion Generator

During the course of the study a need arose for a six degree of freedom washout circuit for a landing approach simulation of a VTOL aircraft. However, there was not sufficient time to compare which circuit might be best for the task, nor even to make parametric studies on the circuit chosen.

As a result of these factors, the washout circuit employing traditional techniques extended to six degree of freedom was selected. This selection was made as a result of confidence in these techniques from other related studies. The circuit used was a particular choice of parameters for the configuration shown in Figure 4.6. Also the lead networks for compensating for simulator lags were added in the manner discussed in Appendix A.

Figure B.1 illustrates this particular washout configuration in analog form. Actually, all of the calculations indicated were done digitally. Calculation cycling rates were sufficiently high in the computer such that the continuous analogy of Figure B.1 is appropriate.

As may be noted on the figure, the specific force at the pilots cockpit is fed through the high pass second order filter in cab reference. This is the dominant part of the translational drive washout. The very low gains around the double integration provide an inertial washout which prevents drifts from accumulating. The cross product residual tilt calculation used f_{cg} rather than f_c . This choice was made since f_{cg} is a smoother varying quantity.

Discussions with pilots who flew the simulation indicated the following.

- 1) The feel in the longitudinal channel was good and quite representative of real flight of the aircraft.

- 2) The lateral channel was good for modest turn entries, however, some undesired forces were noticed on recovery from turns. It is believed that the objection cited in (2) above would not exist with the coordinated washout discussed in Section 4.5. It is very possible that some refinement in the constants of Figure B.1 would also remove this objection. As was mentioned however time did not permit any of the factors to be studied.

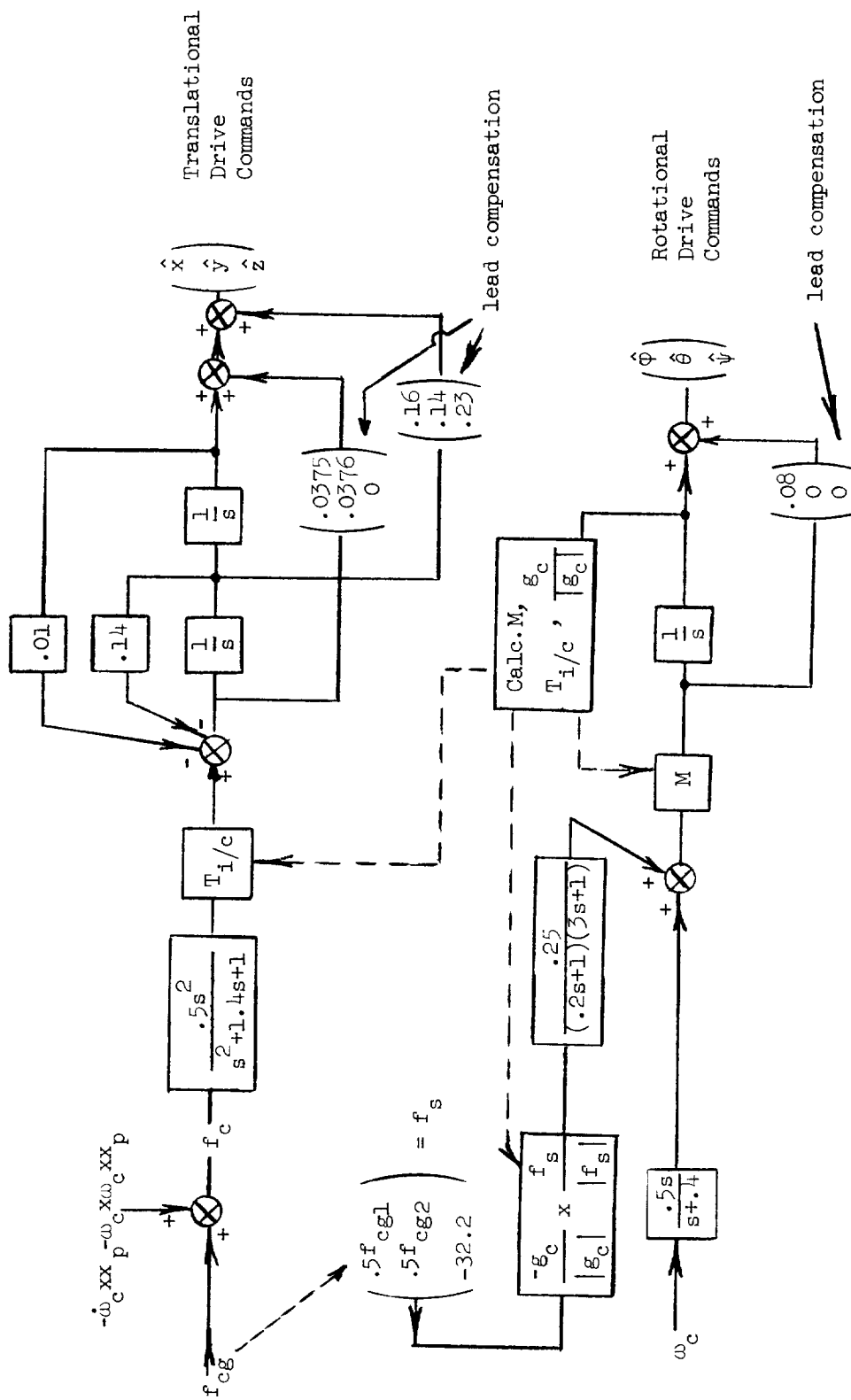


Figure B.1. Six Degree of Freedom Washout Circuit for Ames All-Axis Motion Generator.

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